Fall 1999

A study of sound attenuation using sonic energy focussed at an artificial soil fracture

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ABSTRACT

A STUDY OF SOUND ATTENUATION USING SONIC ENERGY FOCUSSED AT AN ARTIFICIAL SOIL FRACTURE

by
Minhaz Bootwala

Several laws have been passed over the past two decades to control contamination and to remediate already existing contaminated sites. There are a large number of these sites and several *ex-situ* and *in-situ* techniques have been developed to decontaminate these sites. These techniques can be quite expensive, especially the ex-situ clean-up operations, and there has always been a need for cheap, quick remediation methods.

This study investigates the attenuation of sound used in the *in situ* remediation technique coupling Sonic Energy with Pneumatic Fracturing and Vapor Extraction. Preliminary attenuation studies were performed in the laboratory with a microphone made at Lucent Technologies. The laboratory facilities at Lucent Technologies and at the Otto York Center at New Jersey Institute of Technology were used to measure the attenuation of sound through air with five whistles. The best whistle gave a sound intensity at the source of 150 – 160 dB and this whistle was used in the field study. The field study was performed at a site in Hillsborough Township, New Jersey contaminated with trichloroethylene and dichloroethylene where Kaleem (1999) had observed a considerable increase in the removal rate of the contaminants at the site using sound energy, thus lowering the effective remediation time of the site. In this study, experimental runs were performed in which sonic energy of known intensity was applied at the inlet of artificial soil fractures present at the site and its intensity was measured at the outlet of the fractures thereby giving the attenuation of the sound in the soil/rock.

The results obtained indicate that the sonic energy is absorbed very quickly in the ground and hence the sound attenuates very quickly at this site. This rapid attenuation is probably due to the increased attenuation that takes place in rock/soil at this site depending on the nature of the fractures in the rock and soil. A probable theory to explain the increased removal rate of the contaminants even though the sonic energy is absorbed rapidly is that most of the sonic energy is absorbed in a local region near the source, lowering the concentration of the contaminants in that region. This concentration would be lower than that if only air without sound were being used for Vapor Extraction. The rapid depletion of contaminants using sonic energy would result in a higher contaminant concentration in the effluent stream for constant air flowrate. This depletion of contaminants sets up a greater concentration gradient between the remediated region and the contaminated region and hence greater mass diffusion between the two regions. Thus, there is a lowering in the overall concentration of the contaminants in the field and a decrease in the remediation time of the site.

It is recommended that a laboratory model of the fracture and its environment be simulated and attenuation studies be performed to examine the factors that affect the propagation of sound. It is, furthermore, recommended that controlled attenuation studies be made in a bed of soil with the microphone placed in boreholes at closer distances to the sound source. The larger fixed borehole distances at the Hillsborough site would not allow a quantitative indication of how rapidly the sound intensity decreased. A whistle or a siren with a higher intensity and a higher frequency should be designed and used to examine the attenuation that takes place at this site with larger borehole diameters.

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A Masters Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Chemical Engineering

Department of Chemical Engineering, Chemistry and Environmental Science

January 2000

APPROVAL PAGE

A STUDY OF SOUND ATTENUATION USING SONIC ENERGY FOCUSSED AT AN ARTIFICIAL SOIL FRACTURE

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This thesis is dedicated to my beloved family
for their unending love and encouragement.

ACKNOWLEDGMENT

I start by expressing my sincere appreciation to my advisor, Dr. Deran Hanesian for his dedication, patience, and wisdom throughout the length of this study and the preparation of this thesis, and without whose guidance this research would not have been possible. I am grateful to Dr. Angelo Perna and Dr. John Schuring, who served as my committee members, for their inspirational and timely support, technical expertise, and acuity throughout the duration of the project.

I deeply appreciate the technical and active support given to me by Tom Boland who became a good friend during the course of this study. I would also like to thank my fellow students, Heather Hall, Navneet Kumar, Jannina Alvarez, and Peniel Ortega for their continuing support and constructive criticism. A special mention has to be made of Dr. Gary Elko at Lucent Technologies for his expertise in the field of Acoustics and for all of his help in developing the microphone, for his help during the laboratory tests, and for the use of his resources and equipment. Without his help this study could not have been made.

TABLE OF CONTENTS

Chapter **Page**

TABLE OF CONTENTS
(Continued)

Chapter **Page**

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

Chapter | Page

TABLE OF CONTENTS
(Continued)

Chapter **Page**

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES
(Continued)

Figure **Page**

LIST OF FIGURES
(Continued)

Figure **Page**

LIST OF FIGURES
(Continued)

Figure **Page**

LIST OF SYMBOLS

A	=	Mechanical Damping Coefficient (kg/m^3-s)
A_p	=	Amplitude of the sound wave (m)
B	=	Adiabatic Bulk Modulus of Elasticity ($kg/m\text{-}s^2$)
c	=	Velocity of sound (m/s)
c_p	=	Specific heat capacity at constant pressure (J/kg-K)
c_v	=	Specific heat capacity at constant volume (J/kg-K)
G	=	Shear modulus in solids ($kg/m\text{-}s^2$)
i_θ	=	Angle of incidence (deg)
I	=	Intensity of the sound (kg/s^3 or $Watt/m^2$ or dB)
I_0	=	Standard reference Intensity (kg/s^3 or $Watt/m^2$)
m	=	Mass per unit length of a string (kg/m)
M	=	Molecular weight of the gas (g/moles)
N	=	frequency (Hz or cycles/s)
P	=	Pressure of the sound wave (N/m^2 or $kg/m\text{-}s^2$)
P_0	=	Base acoustic pressure (N/m^2 or $kg/m\text{-}s^2$)
r	=	radius of spherical wave (m)
r_t	=	radius of tube (m)
r_θ	=	Angle of reflection (deg)
r_c	=	Critical angle of refraction (deg)
R	=	Universal Gas constant (J/mole-K)
S	=	Source Intensity level (kg/s^3 or $Watt/m^2$ or dB)
T	=	Absolute temperature of a gas (K)

LIST OF SYMBOLS
(Continued)

v	=	Volume of the gas (m^3)
v'	=	Particle velocity (m/s)
v_0	=	Original volume of the gas (m^3)
V	=	Volume of unit mass (m^3/kg)
Y	=	Young's Modulus of Elasticity (kg/m-s^2)
α	=	attenuation coefficient (1/m)
α_θ	=	Coefficient of cubical expansion (1/K)
α'	=	attenuation coefficient (dB/m)
γ	=	Ratio of specific heat capacities, c_p/c_v
κ	=	Appropriate elastic constant of a medium (kg/m-s^2)
κ_θ	=	Coefficient of isothermal elasticity (kg/m-s^2)
κ'	=	Elastic constant of a solid (kg/m-s^2)
λ	=	wavelength of the sound wave (m)
ν_1	=	kinematic viscosity (m^2/s)
ρ	=	Normal density of a medium (kg/m^3)
ρ_0	=	Original density of the gas (kg/m^3)
σ	=	Poison's ratio
τ	=	Force applied on string (Newton)

CHAPTER 1

INTRODUCTION

1.1 Overview

The dumping of hazardous wastes, including chemicals, because they pose a danger to humans, animals, and the environment, was common practice before 1976. Consequently, there are a large number of contaminated sites in the United States. To deal with this contamination, a series of laws have been introduced over the last two decades. For example, the Resource Conservation and Recovery Act (RCRA) of 1976 regulated industries associated with creating, transporting, treating and disposing of hazardous waste and also prohibited the dumping of hazardous wastes on open areas; and the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) of 1980 which the hazardous sites and the responsible parties were identified and feasibility studies and remedial action were taken. Effort has also been made to undo the effect of the contamination and to clean up the contaminated sites by various remediation technologies, some of which are listed below.

1.1.1 Current Remediation Technologies

There are two major Remediation techniques to remove the contaminants from the soil which are *ex situ* and *in situ* techniques.

1.1.1.1 *Ex Situ* Techniques: These techniques involve excavating and transporting the contaminated soil to a remediation unit where the soil is appropriately treated to remove the volatile organic compounds and may be returned to the original site or placed elsewhere. This entails a higher cost of operation than *in situ* techniques.

Some of the *ex situ* methods include, (Kaleem, 1999):

- Thermal Treatment - Involves high temperature (1200°C or more) treatment
- Secure Landfill - A secure landfill holds the contaminated soil in a highly concentrated form for an indefinite period.
- Codisposal - Involves the codisposal of hazardous waste with municipal refuse
- Hazardous Waste Treatment Facility - Chemical and Physical treatment methods, incineration and landfilling of the residues generated from these methods are the most common types of hazardous waste treatment processes

1.1.1.2 *In Situ* Techniques: These techniques involve treating the contaminated soil on the site where it is found without excavating the soil. Thus, it tends to involve lower costs than *ex situ* techniques.

Some of the *in situ* methods include, (Kaleem, 1999):

- Washing - This method is a common treatment method used mostly for permeable soils contaminated with solid and liquid waste. It involves treating the site with a solution that is able to dissolve the contaminants in the soil. The major advantages of this technology are the ability to remediate the site permanently and the moderate cost involved in implementing the technology. The major disadvantage of this technique is the fact that it can only be utilized in highly permeable soils.

- Chemical Treatment - The commonly used chemical treatment processes are oxidation and reduction reactions, pH adjustments and ionic exchange and chemical fixation.
- Bioremediation - It is employed mainly for low concentrations of toxic substances and involves the use of aerobic or anaerobic microorganisms to decompose the waste.
- Pneumatic Fracturing followed by Vapor Extraction - This method has proven to be an effective technique especially for tightly packed soils. The pneumatic fracturing loosens up the soil and provides passages (fractures) through which more vapor can pass in vapor extraction methods, to remove the contaminants by desorption and facilitate a higher removal rate from the soil.
- Sound Energy - Remediation of subsurface soils using sound energy is currently under development as an *in situ* technology. Sound energy is used as an enhancement technique for other methods of treatment wherein the sonic energy increases the removal rate of the contaminants from the soil.

1.1.2 Using Sonic Energy

Sonic Energy is used to enhance the performance of other methods of treatment. The sonic energy is especially used for tight soils where it loosens up the particles of the soil by providing a vibrational motion to the particles. Thus, it is used to increase the permeability of the soil so that other remediation agents (such as chemicals and microorganisms) can have easy passage through the soil being remediated. This leads to a faster rate of remediation because there is more contact between the remediation agent and the hazardous waste in the soil, (Fernandez, 1997).

Some of the applications of sound energy include, (Kaleem, 1999):

- The enhancement of chemical treatment processes during the decontamination of soils.
- The elimination of microbes using ultrasonic energy. These microbes could decrease the permeability of the soil by clogging the pore spaces of the soil.
- The improvement in the permeability of tightly packed clays. This can be achieved by using the ultrasound to disperse the tightly packed clay formation.

Some of the existing methods for cleaning up sites contaminated with hazardous wastes are time consuming and expensive. Pneumatic Fracturing and air injection have been successfully used to clean up a site in Highland Park, New Jersey. This site was contaminated with trichoroethylene and the remediation time was reduced from 10 to 2 years, (Fernandez, 1997). Coupling Pneumatic Fracturing, Vapor Extraction and Sonic Energy has been proven to further reduce the remediation time and can help to achieve the regulatory specifications faster, thus reducing the cumulative cost involved in a site cleanup, (Kaleem, 1999). This improvement in remediation time justifies further investigation of the appropriate location of the extraction wells around the injection well to make the process more effective.

1.2 Research Objective

This field research is based on earlier laboratory work, which showed that sonic energy enhances the removal of volatile organic contaminants, specifically ethanol and water, from a tank packed with sand using a geotextile as a simulated fracture, (Fernandez, 1997). This was further tested by field research in which sonic energy was coupled with pneumatic fracturing and vapor extraction to remove trichloroethylene and dichloroethylene at the Derelco industrial site in Hillsborough, New Jersey. The results obtained clearly indicate a marked increase in the removal rate of the trichloroethylene, (Kaleem, 1999) The objective of the research presented in this document is to test the attenuation of the sonic energy as it moves through the fractures and is absorbed by the soil. This will help determine the approximate distance from the injection borehole, where the extraction boreholes should be drilled for effective removal of the contaminants.

CHAPTER 2

BACKGROUND OF THE STUDY

2.1 Overview of Acoustics

Sound, in the true sense, is a compressional wave that produces a sensation in the human ear. The average human ear will respond to frequencies ranging from 20 Hz (cycles per second) to 20,000 Hz. The frequency range below the audible range is called the infrasonic range of frequencies, the audible range is called the sonic range and the range of frequencies above the audible range is called the ultrasonic range.

Sound is propagated through a medium as a compressional wave which means that the medium will be alternately compressed and rarified as the wave moves through it and the particles of the air will move back and forth parallel to the propagation of the sound wave. When the medium is compressed its pressure will increase above the steady state pressure, and when it is rarified its pressure will decrease to a value below that of a steady state pressure. The sound pressure is determined by the variation in pressure that takes place as the sound wave passes a point in the medium. The sound pressure is quite an important factor since many of the available sound detecting devices including the human ears respond to the sound pressure.

A sound wave is basically a mechanical wave, which is defined as a disturbance from some equilibrium position in a homogeneous continuous material. This mechanical wave diminishes in strength as it moves through the medium, away from the point of origin. Mechanical waves can be categorized as transverse waves, where the motion of the particles is perpendicular to the direction of propagation of the wave, and longitudinal waves, where the motion of the particles is in the direction of the propagation of the wave. Sound waves in gases and liquids are longitudinal waves whereas those in solids could be either transverse or longitudinal waves. Mechanical waves do not transport any matter but transport only energy along the medium and cannot travel in space since they require a medium to travel in. Another characteristic of sound is the fact that if an observer is moving relatively to the source of sound, the frequency observed differs from the frequency emitted. This is called the Doppler effect.

Sound waves can also be classified into two categories, one in which the material is strained within the elastic limit (i.e., Hooke's Law holds) and the other in which the material is strained beyond the elastic limit. The first type of wave is called an elastic wave; these are responsible for most of the observed acoustic phenomena. The second category of waves covers such phenomena as shock waves and high energy ultrasonic propagation.

2.1.1 Velocity of Sound

The motion of a vibrating body is transferred to an elastic medium with which it is in contact thus producing longitudinal waves. The velocity with which these waves travel through the medium is dependent on the fundamental physical quantities, elasticity and density. This is independent of the velocity of the source of the wave with respect to the medium of transmission. The velocity c of the sound wave in a medium is given by, (Wood, 1941):

$$c = \sqrt{\frac{\kappa}{\varrho}} \qquad (2.1)$$

Where κ is the appropriate elastic constant and ρ is the normal density of the medium.

It is important to note that the variations of density involved in the transmission of the wave are always small compared with the medium density ρ; otherwise Equation 2.1 is no longer valid. The elastic constant, κ, is the bulk modulus of elasticity, B, in the case of a fluid medium. Solids, however, change in shape as well as in volume, consequently the coefficient of rigidity or Shear modulus, G, must be introduced and κ is replaced by κ'+4G/3, (Wood, 1941).

2.1.2 Velocity of Sound in Gases

Equation 2.1 is modified for gases by substituting the constant B, the adiabatic Bulk Modulus of Elasticity, in place of κ, (Wood, 1941):

$$c = \sqrt{\frac{B}{\varrho}} = \sqrt{\frac{\gamma P}{\varrho}} = \sqrt{\frac{\gamma RT}{M}} \quad \text{(ideal gas)} \tag{2.2}$$

Where P is the pressure of the sound wave at density ρ, R is the Universal Gas constant, T is the absolute temperature, M is the molecular weight of the gas and γ is the ratio of specific heat capacities, c_p/c_v. For air, this value is 1.4. The derivation of this equation is given in Wood, 1941. This equation gives the velocity of sound in atmospheric air as 331.5 meters per second or 1100 feet per second at 0°C. The bulk modulus of elasticity, B, is given by, (Wood, 1941):

$$B = v_0 \frac{dp}{dv} = \varrho_0 \frac{dp}{d\varrho} \tag{2.3}$$

Where v_0 and ρ_0 are the original volume and density of the gas respectively.

Since the relationship between pressure and density is constant for a given temperature, the change in pressure has no influence on the velocity. However, the density of a gas changes with temperature at constant pressure, and hence another relationship between the velocity of sound and temperature (also derived from Equation 2.2) is defined as, (Wood, 1941):

$$c \propto \sqrt{T} \tag{2.4}$$

That is, the velocity c varies directly as the square root of the absolute temperature T.

The velocity is only slightly affected by the humidity of the air. The presence of water vapor produces a slight lowering of the mean density whereas the value of the ratio of specific heats practically remains the same.

2.1.3 Velocity of Sound in Liquids

The same relation given by Equation 2.2 for the velocity of sound in a gas is equally applicable for liquids. For some liquids e.g. water, γ can be neglected when the difference between isothermal and adiabatic volume elasticity is small but in other liquids e.g. ethyl ether, the constant γ can have a significant effect. The ratio of specific heats, γ, for liquids can be calculated by the equation, (Wood, 1941):

$$\gamma = \frac{1}{1 - \alpha_\theta^{\ 2}\kappa_\theta \mathrm{VT} / c_p} \tag{2.5}$$

Where α_θ is the coefficient of cubical expansion, κ_θ is the coefficient of isothermal elasticity, V is the volume of unit mass, T is the absolute temperature and c_p is the specific heat at constant pressure.

2.1.4 Velocity of Sound in Solids

The transmission of waves through fluids is relatively simple since only longitudinal waves are generated. Transverse waves are not possible since a perfect fluid will not transmit shearing forces. In solids, however, which readily transmit both compressional and shearing forces, both longitudinal and transverse waves may be set up. Some of the important cases where this is seen are, (Wood, 1941):

(1) Transverse waves in wires, $c = (\tau/m)^{1/2}$, in which the elastic properties of the material may be disregarded; τ is the force applied in stretching the string and m is the mass per unit length.

(2) Transverse waves in bars, $c \propto (1/\lambda)\ (Y/\rho)^{1/2}$, the velocity depending on the wavelength λ, as well as on the Young's Modulus Y, and the density ρ of the material.

(3) Longitudinal waves in wires and bars, $c = (Y/\rho)^{1/2}$

In general, "when a longitudinal wave is propagating through an isotropic solid, the speed of sound is related to the amount of compression that the material can endure. For solids having a finite area, the speed of sound is related to the Young's Modulus of Elasticity Y by the following equation," (Blitz, 1964):

$$c = \sqrt{\frac{Y}{\varrho}} \tag{2.6}$$

"For solids having large areas of cross-section, a uniform compressional stress and shear stress is created under compression. Thus, the elastic modulus contains a rigidity component given by G, the shear modulus, and is given by", (Blitz, 1964):

$$\kappa = \kappa' + \frac{4G}{3} = \frac{Y(1-\sigma)}{(1+\sigma)(1-2\sigma)} \tag{2.7}$$

Here, Y is the Young's Modulus and σ is Poison's ratio. The velocity of sound is given by substituting Equation 2.7 in Equation 2.1.

When shear stresses are applied to a solid, shear or transverse waves are propagated. The value of the shear velocity is given by the expression, (Blitz, 1964):

$$c = \sqrt{\frac{G}{\varrho}} \tag{2.8}$$

2.1.5 Acoustic Intensity

Acoustic Intensity is defined as the average rate of flow of acoustic energy through unit area, or the acoustic power flow through unit area. The sound intensity is given by, (Albers, 1970):

$$I = \frac{P^2}{\rho c} \tag{2.9}$$

where P is the sound pressure, ρ is the density of the medium, c is the speed of the sound in the medium and ρc is the Characteristic or Acoustic Impedance .

In terms of particle velocity, v', the equation becomes, (Albers, 1970):

$$I = Pv' \tag{2.10}$$

Equating Equations 2.9 and 2.10, gives the characteristic/acoustic impedance, ρc,

$$Pv' = \frac{P^2}{\rho c} \tag{2.11}$$

$$\rho c = \frac{P}{v'} \tag{2.12}$$

Equation 2.9 shows that the intensity of sound waves is directly proportional to the square of the sound pressure for the same characteristic impedance. The intensity is also shown to be directly proportional to the square of the amplitude, A_p, by the equation, (Fernandez, 1997):

$$I = \frac{1}{2} c \left(\frac{2\pi}{\lambda} \right)^2 B A_p^2 \tag{2.13}$$

Where λ is the wavelength and B is the Bulk Modulus of Elasticity.

Because of the tremendous variation of intensities occurring in normal sound phenomena and also because of the characteristics of the human ear, it is convenient to express the sound intensity on a logarithmic scale. This scale is called the **decibel** scale, where the intensity is calculated with reference to some standard intensity, I_0, generally taken as 10^{-12} watt/m^2 (Albers, 1970), which is approximately the lower threshold of human hearing. The decibel scale is so arranged such that a sound intensity 10 times as great as another sound intensity differs from it by 10 dB. In addition, doubling the intensity ratio always produces the same decibel difference regardless of the position in the scale. Thus, the sound intensity in decibels is expressed as, (Hunter, 1957):

$$I\,(\mathrm{dB}) = 10 \log_{10} \frac{I}{I_0} \tag{2.14}$$

Where I and I_0 have the same units of intensity e.g. watt/m^2. On this scale, zero represents the intensity of the softest sound that the human ear can detect (10^{-12} W/m^2), and 100 is the intensity of a sound that is ten trillion times as strong. Here are some typical measurements in the decibel scale; the rustle of leaves, 10 dB; ordinary conversation 40 to 70 dB, a pneumatic drill 90 dB; an airplane engine 100 to 120 dB. A sound intensity of 130 dB is not observed as sound by the ear but is felt as pain instead.

As seen above in Equation 2.9, the intensity is proportional to the square of the pressure for the same characteristic impedance. Thus, the intensity level in decibels may be expressed as, (Hunter, 1957):

$$I\ (\mathrm{dB}) = 10 \log_{10} \frac{P^2}{P_0^2} = 20 \log_{10} \frac{P}{P_0} \tag{2.15}$$

Where P_0 is the base acoustic pressure. A few simple equivalents (based on Equations 2.14 and 2.15) which are useful to remember when thinking of intensities in terms of decibels are that a level of 3 dB corresponds to an intensity ratio I/I_0 of 2:1 (3 dB = 10 $\log_{10} I/I_0$, a level of 6 dB an intensity ratio of 4:1 (pressure ratio of 2:1), a level of 10 dB an intensity ratio of 10:1, and a level of 20 dB an intensity ratio of 100:1 (pressure ratio of 10:1)

2.1.6 Divergence

It has been commonly observed that under normal conditions, the intensity of the sound rapidly diminishes as one moves away from the source. This can be explained by using the Principle of Conservation of Energy. As defined previously, the intensity is given by the energy of the wave per unit area. In a wave expanding as a sphere, as the wave-front expands, the total energy remains constant while the area of the spherical wave-front changes, say from $4\pi r_1^2$ at a radius of r_1 to $4\pi r_2^2$ at a radius of r_2 with the corresponding intensities being I_1 and I_2 respectively. Therefore, equating total energy gives, (Richardson, 1935):

$$I_1 4\pi r_1^2 = I_2 4\pi r_2^2 \tag{2.16}$$

and

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2} \tag{2.17}$$

or, (Officer, 1958)

$$I = S\left(\frac{1}{r^2}\right) \tag{2.18}$$

Where S is the source level. Using Equation 2.14,

$$I\ (\mathrm{dB}) = S\ (\mathrm{dB}) - 20 \log_{10} r \tag{2.19}$$

Where 20 $\log_{10}$ r is called the spreading loss.

Thus, as can be seen, there is a decrease in intensity with distance due to divergence. The intensity is directly proportional to $1/r^2$, which means that if the distance r from the source is doubled the intensity will be one-fourth as great. On the decibel scale, each time the range is doubled the intensity will decrease due to divergence by 6 dB. Two remarks need to be made here. First, this analysis assumes a point-origin of sound, which is not true in practice, and hence for distances that are comparable to the dimensions of the source of sound, this equation will not hold true. At large distances, however, this equation is perfectly applicable. Secondly, this analysis does not take into account the attenuation in sound due to loss of energy dissipated in friction and hence heat.

2.1.7 Reflection

When a beam of plane waves is incident normally to a plane boundary separating two semi-infinite isotropic homogeneous media, part of the incident sound energy is reflected back along its original path and the remainder is transmitted into the other medium, thus accounting for reflection and refraction respectively as in light. The sound wave-front encounters a surface where there is great change in the value of the acoustic impedance and hence will be reflected. The law of reflection so common in light analysis applies to sound. This law states that the angle which the incident ray makes with the normal to the surface is equal to that made by the reflected ray:

$$i_\theta = r_\theta \tag{2.20}$$

Where i_θ is the angle of incidence and r_θ is the angle of reflection.

2.1.8 Refraction

When a wave front for any type of wave passes from a medium, where the velocity of propagation is c_1 to another medium where the velocity of propagation is c_2, the direction of the rays will be changed unless they are perpendicular to the surface.

Refraction may be shown to follow the same laws as light, i.e., if i is the incident angle in a medium where the velocity of sound is c_1, and r is the refracted angle in the second medium where the velocity is c_2, then, (Richardson, 1935):

$$\frac{\sin i_\theta}{\sin r_\theta} = \frac{c_1}{c_2} = \text{a constant} \tag{2.21}$$

The critical angle, r_c, is again given as

$$\sin r_c = \frac{c_1}{c_2} \tag{2.22}$$

If the angle of incidence is greater than the critical angle, the sound wave is completely reflected back to the media it came from and no transmission takes place.

2.1.9 Diffraction

Diffraction or bending is a property of wave motion which occurs when waves are passed through an aperture or when they are obstructed by some object placed in their path. Diffraction is also associated with the finite size of a source. The assumption that light and sound travel in straight lines is not always true, especially in the case of sound. This is the reason why sound can be heard around corners. For spherical waves, according to the Principle of Huygens, every point on a wave-front becomes the origin of secondary waves as it vibrates; so that the wave-front at a succeeding instant is an envelope of these secondary waves. When an obstacle that will not allow the sound to pass, is placed across the path of the waves, secondary waves arising from the front still are audible, although the intensity of the sound received is less than it would have been, had the obstacle been absent. For plane waves, the deviation of energy from the parallel beam is due to diffraction.

2.1.10 Scattering

When the dimensions of an obstacle in the beam are small compared with the wavelength, scattering of the waves will take place. "For a spherical obstacle, the amount of energy lost increases in proportion to the fourth power of the frequency. This is known as Rayleigh Scattering, which is responsible for the attenuation of ultrasonic waves by small particles in suspension in fluids and by the grain structure in polycrystalline solids," (Blitz, 1964). "Scattering is the main cause of attenuation of a sound wave when traveling through soil or other heterogeneous materials and it increases as the third power of the grain size as long as the grain size remains smaller than the wavelength of sound wave," (Fernandez, 1997).

2.1.11 Absorption

Absorption is another factor which affects the propagation of sound and its effects vary with frequency. Generally, the tones of shortest wave-length are most affected. The mechanism of the absorption is similar to that produced by the scattering of light waves in a turbid fluid. This type of absorption becomes most conspicuous as the wave-length approaches the average size of the particles forming the medium. The propagation of sound through narrow channels is attended by rapid reduction of amplitude, by reason of the energy lost in friction. The effects of viscosity and heat conduction in degrading the sound energy are greatly increased when a gaseous medium (air, for example) is brought into contact with a large surface area of solid or liquid. "The viscous forces are increased because the tangential motion of the gas layers is hindered by the proximity of the solid wall," (Wood, 1941). The smaller the radius of the cavity the greater are the viscous forces and the more rapidly is the sound energy absorbed as it passes along the cavity. This is the accepted explanation of the true absorbent qualities of porous materials. The absorption is a function of the size of the pores, and a geometric factor of the length of the pores. The intensity thus falls in passing through a material according to the exponential law, (Richardson, 1935):

$$I = I_0 \exp(-\alpha r) \tag{2.23}$$

The intensity of the wave thus theoretically falls to zero when the distance r is infinity.

For narrow tubes or cavities, the attenuation coefficient, α, can be expressed by the following equation, (Wood, 1941):

$$\alpha = \frac{2\sqrt{\nu_1 \gamma 2\pi N}}{c r_t} \tag{2.24}$$

The attenuation coefficient, α, therefore, varies directly as the square root of the product of kinematic viscosity ν_l, the ratio of specific heats γ, and the frequency N, and varies inversely as the product of the velocity of sound c and the radius of the tube r_t. To provide an example of the rate of absorption that takes place in pores or narrow tubes, taking standard values for air as $\nu_l = 0.13 \times 10^{-4}$ m^2/s, $\gamma = 1.41$, $c = 330$ m/s and at a frequency of 1000 cycles per second, the attenuation coefficient in a tube of radius 0.00001 m is therefore $\alpha = 2.05$ with the amplitude falling to 1/e of its initial value in 0.005 m approximately, (Wood, 1941).

2.1.12 Sound Attenuation

When energy is propagated as waves through a medium, some of the energy is lost due to viscosity, heat conduction, scattering, and diffraction. With absorption, the sound energy is converted into heat by internal friction in the medium and is therefore lost. This loss of energy is in addition to the decrease in intensity due to divergence.

In real fluids, tangential stresses are developed due to the viscosity of the fluid, which tend to damp out relative motion between the various parts of a fluid. This relative motion or friction produces a loss of sound energy, which is converted to heat.

Another factor that cannot be neglected is the loss of energy due to heat conduction in the medium. For waves of very low frequency, the attenuation of this nature is negligible whereas for waves of very high frequencies, the effects of viscosity and heat conduction are much more serious and cannot be neglected. Thus, the attenuation is much more prominent due to these effects. For intermediate frequencies, the effect is a partial stifling of the wave. The amplitude of the wave also affects the attenuation of sound. The loss of heat in this case is due to the transfer of heat from the regions of higher pressure (compression) to those of lower pressure (rarifaction), the tendency being to produce equalization of pressure, i.e. to suppress the wave. Such effects become more serious at large amplitudes, that is, near to the source. Thus, the intensity rapidly diminishes at first near the source, then more slowly as the distance increases. On such grounds, sources of small intensity and large area are likely to be more efficient than sources of great intensity and small area.

Another factor having an important influence on sound absorption in gases is the presence of water vapor, which has a marked effect on the rate of decay of the sound vibrations. The observed absorption in moist air is 10 to 100 times that in dry air. As the concentration of the impurity is varied, the sound absorption in a gas at a particular frequency passes through a maximum. In general, the effect of impurities in gases may have an important influence on the absorption.

Another mechanism by which sound attenuates especially at higher frequencies is thermal relaxation. The absorption or attenuation coefficient increases due to the intermolecular transfers of vibrational energy from the wave to the internal kinetic energy of the gas thereby damping the wave.

Attenuation in solids also occurs due to grain and domain boundary effects, interstitial atom diffusion, ferromagnetic and ferroelectric effects, interactions between sound waves and electron motion, and interactions between sound waves and lattice vibrations.

The attenuation in decibels is expressed as the product of the attenuation coefficient, α' expressed in dB per yard or dB per meter, and the corresponding distance r in yard or meter respectively. Thus, the intensity at any range due to an initial intensity I is expressed as, (Officer, 1958):

$$I = S\left(\frac{1}{r^2}\right)\exp(-\alpha r) \tag{2.25}$$

Where S is the source level. In decibels, (Officer, 1958),

$$I\ (\mathrm{dB}) + 20 \log r = S\ (\mathrm{dB}) - \alpha' r \tag{2.26}$$

A plot of the measured intensity in decibels plus the spreading loss, 20 log r, versus r will be a straight line whose slope is -α', the excess loss in decibels per unit distance. This does not take into account the loss in intensity due to refraction although the effect of refraction is negligible over short ranges.

The attenuation coefficient can also be given by, (Hunter, 1957):

$$\alpha = \frac{a}{2\rho c} \tag{2.27}$$

which gives α, the attenuation coefficient, in terms of a, the mechanical damping coefficient.

2.1.13 Acoustic Properties of Soil

The acoustic properties of soil depend to a large extent on the nature of the soil. The porosity, moisture content, type of minerals present and the state of consolidation of the soil affect the acoustic properties of soil, for example, the speed of sound, the amplitude of sound waves and the attenuation of sound in the soil, (Blangy et al, 1993). Tightly packed clays can be considered as homogeneous materials since sound waves travel faster and with little change in velocity and also with less attenuation, (Fernandez, 1997). Artificially generated seismic waves provide information about the configuration of rock layers for oil exploration and information of the rigidity of shallow layers for engineering purposes. The propagation of waves in rock and soil is modified by the propagation characteristics of individual rock layers.

Some of the factors that affect the propagation of waves in rock and soil are their non-homogeneity, anisotropy which means that their properties change with direction, and their non-elasticity. The laminar nature, granular content and fluid content affect the homogeneity of rocks. There are several mechanisms by which the attenuation of sound takes place in the ground. For example, the relative motion between the skeleton of a porous rock and the contained fluid could easily account for loss of energy. For a granular rock, any sliding at the points of contact would absorb energy, (White, 1965).

The presence of air in voids in porous soils considerably affects the attenuation of sound and saturating the soil with some liquid reduces the amount of attenuation. Attenuation in geologic materials is often highly frequency dependent. As a general rule, attenuation increases with frequency. Attenuation coefficients in dry sand vary from 0.09 dB/cm at 500 Hz to 10 dB/cm at 16kHz. For a clayey silt, the attenuation coefficients vary from 1.9 dB/cm in the dry state to 1.0 dB/cm near saturation, both values at a frequency of about 1.0 kHz, (Koerner et al, 1981). Figure 2.1 shows the variation of attenuation coefficients with frequency for various materials, while Table 2.1 represents the attenuation coefficients of sound waves for different types of rocks.

In solid rock, mechanical waves can exist in the form of both transverse and longitudinal waves also known as s-waves and p-waves respectively, (White, 1965). The propagation of the wave in the rock depends on the consistency of the shear and bulk moduli. The shear modulus and the bulk modulus depend on the composition of the rock and a change in the composition of the rock produces variation in the shear modulus as well as the bulk modulus.

Figure 2.1 Attenuation Coefficients of different materials
(Source: Koerner et al, 1981, "Acoustic Emission Behaviour and Monitoring of Soils", *Acoustic Emissions in Geotechnical Engineering Practice*, American Society for Testing and Materials, STP 750, pp. 93-141)

Table 2.1 Measured Attenuation Coefficients of Several Rock Types

Rock Type	Frequency (cps)	Attenuation Coefficient (α_p)	Method
Granite:	1×10^6	$0.044\ cm^{-1}$	Multiple reflection of sine-wave train
Kamyk	$(0.2\text{-}2) \times 10^6$	$3.9 \times 10^{-8} f$ sec/cm	Short pulse, direct path only
Limestone: Solenhofen	$(3\text{-}15) \times 10^6$	$5.2 \times 10^{-8} f$ sec/cm	Multiple reflection of sine-wave train
Sandstone: Amherst	1×10^6	$0.035\ cm^{-1}$	Multiple reflection of sine-wave train
Chalk: Chiselhurst	600	$6 \times 10^{-6}\ cm^{-1}$	Bulk medium, sine-wave train
Shale:	$(3\text{-}12) \times 10^3$	$45 \times 10^{-8} f$ sec/cm	Long. Resonance
Sylvan	$(6\text{-}20) \times 10^3$	$4 \times 10^{-6} f$ sec/cm	Bulk medium, Fourier analysis of pulses

(Source: White, J.E., 1965, *Seismic Waves: Radiation, Transmission and Attenuation*, International Series in the Earth Sciences, McGraw-Hill Book Company, Inc., New York, New York)

2.1.14 Sonic Generators

The main types of generators used to produce sound or sonic energy are listed as, (Fernandez, 1997 and Kaleem, 1999):

1. Electrostatic Generators
2. Electrodynamic Generators
3. Magnetostrictive Generators
4. Piezoelectric Generators
5. Pneumatic Generators (Dynamic Generators and Static Generators)

“The principle governing the operation of Electrostatic Generators is that electrostatic forces between the plates of a condenser can change the spacing between the plates .The attraction and repulsion between these plates creates sound vibrations in the air that is near the plates.

The principle that governs the operation of Electrodynamic Generators is that an electric current when passed through a coil will generate a magnetic field which causes vibrations in a magnetic plate. These vibrations produce resonance and hence enhance the sound being generated.

Magnetostrictive Generators use a voltage applied to a metallic material. The material expands when the voltage is applied to it and contracts to its normal shape when the voltage is removed. Thus, when an alternating voltage is applied to the material a series of vibrations are produced. These vibrations produce an acoustic field.

The principle that governs the operation of Piezoelectric Generators is based on the fact that a crystal with piezoelectric properties will build a charge when brought into contact with a voltage. This charged crystal will be attracted to other oppositely charged crystals. When the voltage is reversed the charge on the crystal is also reversed. A series of alternating charges causes the crystal to vibrate. If the vibration of the crystal coincides with its resonance frequency a sound field is generated.

Pneumatic Generators produce sound waves using air. Pneumatic Generators can be divided into two subclasses, Static Generators and Dynamic Generators.

Dynamic Generators operate on the principle that when a rotating device is allowed to interrupt a jet of air intermittently, a sound wave is generated. An example of a Dynamic Generator is a Siren. A major disadvantage of the siren is its susceptibility to mechanical damage due to its moving parts at high revolutions per second.

The principle governing Static Generators is that a jet of air emerging from a converging nozzle, close to the speed of sound, causes waves to form at the tip of the nozzle. When a resonant cavity is placed in the path of the air jet, a sound wave is produced. Whistles are examples of Static Generators. Whistles have a major advantage over sirens in that whistles have no moving parts," (Kaleem, 1999).

For this research, a whistle will be used as the sonic generator. This selection is based on previous laboratory work (Fernandez, 1997) and the fact that the whistle is more mechanically resistant compared to the siren.

2.1.15 Microphones

A microphone is a device that performs the function of converting the sound energy to electrical energy. There is a pressure variation (sound pressure) and there is a particle velocity variation that accompanies the propagation of a sound wave. In order to measure sound levels, it is necessary to convert the sound pressure to an electrical signal that can be amplified and measured. Microphones that respond to the particle velocity are often used in the communication systems but in sound measurement in both liquid and gas media, pressure microphones are nearly always used.

The main type of microphones are listed as:

1. The moving-coil microphone
2. The Capacitor Microphone
3. The Crystal Microphone

4. The Ribbon Microphone or the Velocity Microphone
5. The Carbon Microphone

In the moving-coil microphone, the voltage-generating element, in the form of a helical coil, is suspended in the air gap of a radial magnetic field by rigid attachment to a piston-like diaphragm. The acoustic pressure acting on the diaphragm produces a motion in the coil which generates a voltage that is proportional to the pressure.

In the capacitor microphone the moving element is an elastic metal diaphragm which responds to the variations of the sound field with flexure. The diaphragm is made one of the plates of a parallel-plate capacitor, the other plate being rigidly fixed. Since the capacitance of a parallel-plate capacitor is inversely proportional to the distance between the plates, the capacitance can be made an essentially linear function of the displacement. This displacement is proportional to the pressure of the sound wave that the diaphragm senses.

The crystal microphone operates by the principle of piezoelectricity. Two piezoelectric crystals are sandwiched together to form the voltage generating element called the bimorph element. The bimorph element is subjected to bending by the acoustic pressure which impinges on the diaphragm. This displacement in the crystal element produces a change in the voltage by the principle of piezoelectricity. This voltage is then calibrated to give the intensity.

The ribbon microphone is similar to the moving-coil microphone in that the voltage generating element is a moving thin metallic ribbon open to the sound field on both faces suspended between the pole pieces of a magnet, and therefore, the output voltage is proportional to the velocity of motion of the ribbon. Sound waves incident on the front also act on the back of the ribbon but the pressure on the back of the ribbon is delayed because the waves take time to travel around the pole pieces. However, unlike the moving-coil microphone, it is designed as a mass-controlled system, which means that the ribbon is made to behave like a mass in order to make the velocity of the ribbon directly proportional to the particle velocity in the plane sound wave. This is done by locating the fundamental resonance of the ribbon at very low frequencies, so that it will behave like a mass throughout the entire frequency range, (Beranek, 1988).

The carbon microphone like the capacitor microphone, in principle, consists of a variable impedance element supplied with a polarizing voltage and controlled by the acoustic pressure. The variable element is a cell of carbon grains. One of the faces of this cell is a flexible membrane, which is exposed to the sound field. The alternating pressure of the sound wave causes vibrations in the total resistance of the order of 0.1 per cent, the resistance being inversely proportional to the displacement of the diaphragm.

2.2 Pneumatic Fracturing and Vapor Extraction

The base of this research rests on a technology developed by The Hazardous Substance Management Research Center (HSMRC, NJIT) for the remediation of tightly packed soils. This method, known as Pneumatic Fracturing, was proven to be effective in increasing the permeability of the soil, (EPA/540/AR-93/509, July 1993). Fractures are made in the soil by passing a high-pressure pulse of air or nitrogen (around 250 - 500 psi depending on the depth of the fracture to be made) for less than a minute through the soil at the fracture depth. The region around the fracture zone is sealed by using inflatable packers. Due to the high pressure of the gas and the blockage of all other outlets, the pulse is forced to pass through the soil as a result of which it creates fractures in the soil. It is believed that the existence of these fractures enhance the passage of vapor in the vapor extraction process and also results in the release of contaminants in the soil, which would otherwise have been trapped. The effect of this technology has been greatly enhanced by coupling it with a long existing concept of drying by vapor extraction. When air is injected into a formation it will travel through the path that offers the minimum resistance, which in this case is the fracture. The presence of the fractures greatly increases the air flow through the soil. As the air passes through the fracture, due to concentration gradients and pressure differences and the increased air flow rate, the moisture in the fracture will be evaporated and be carried away with the air stream. Thus, the air flowing through the fracture is drying the ground. Using the same drying theory, any contaminants trapped in the soil prior to pneumatic fracturing are also released along with the moisture, thus enabling the clean-up of the site. This was verified by the same study that showed the increase in the permeability of the soil wherein the concentration of the organic contaminant removed was observed to increase, (EPA/540/AR-93/509, July 1993).

2.3 Recent Work done on Project

Using Pneumatic Fracturing and Vapor Extraction combined, further enhancement of performance has been achieved with the application of Sonic Energy. This method, on which this study is based, has been conclusively and repeatedly proven in previous laboratory and *in situ* field studies, (Fernandez, 1997; Lin, 1999; Kaleem, 1999). These studies determined that focusing sonic energy into a fracture with vapor extraction can lead to an enhancement in the removal rate of fluids that are trapped inside tightly packed soils.

2.3.1 Work done by Hugo Fernandez (Fernandez, 1997)

Laboratory studies performed on drying of solids in the presence of a sonic field show that several effects are obtained when a sonic intensity of about 160 dB is allowed to pass through a fracture.

The first effect is the lowering of the net total pressure within the fracture by the compression and dilation of the air within the fracture caused by the sonic energy. These compressions and dilations tend to lower the net total pressure within the fractures because it is known that dilation regions dominate over compression regions. Thus the lower net total pressure causes more of the liquid in the fractures to vaporize and be carried away by the air stream. In addition the lower net total pressure within the fracture causes a pressure gradient to develop which acts as a driving force for liquid to move towards the fractures.

Another effect when a sound field of 160 dB is focused into a fracture is the lowering of the gas – liquid interface film. This is achieved due to the higher turbulence that is built up in the region because of the presence of the sonic field. This decrease in the interface film increases both mass and heat transfer and causes more liquid to be evaporated.

Furthermore, moisture that is trapped within the fractures and separated by air bubbles will be released because the sonic energy causes the bubbles to heat and expand.

The pressure gradient is in the direction of the fracture and hence, the capillary contents move toward the fracture zone.

A last effect that can be obtained when an intense sonic field of 160 dB is focused into a fracture is Cavitation in liquids caused by the intense sound field. It is believed that the effect of Cavitation may have a positive influence on the removal rate of the contaminant.

The laboratory studies that were performed investigated the effect of applying air flowrates coupled with sonic energy in a soil fracture to enhance the removal of volatile organic contaminants in the soil. The results conclusively prove that both means of sonic generation, the siren and the whistle, effectively enhanced the removal rate of the contaminants. The siren showed a 192% improvement and the whistle showed a 931.4% improvement in the concentration of ethanol, the simulated contaminant removed, in the falling rate region of the drying curve. A corresponding decrease of 41% for the siren and 74% decrease for the whistle was observed in the remediation time to reach asymptotic levels. The results also showed that the whistle was much better in performance to the siren in every case that was observed.

2.3.2 Work done by Chin-Yu Lin (Lin, 1999)

The laboratory study investigated the effect of the frequency of the sonic energy applied, coupled with soil fracturing and vapor extraction, on the removal rate of volatile organic compounds from low permeability soils. The sonic generator used was the siren since the frequency of the whistle could not be varied easily. The range of frequencies investigated was from 2,957 to 17,677 and the intensity of the siren was less than 130 dB in the range investigated. The results obtained showed that the effect of frequency within the range mentioned is not significant. Comparing the results with the results obtained by Fernandez, it is believed that the sound intensity is a very important factor in enhancing the removal rate of contaminants. Boucher (1958) has recommended the use of sound energy with frequencies between 7 kHz and 20 kHz and intensity greater than 145 dB for best sonic drying.

2.3.3 Work done by Hassan Kaleem (Kaleem, 1999)

This *in situ* field study was performed at the Derelco site, Hillsborough, New Jersey, contaminated with trichloroethylene and dichloroethylene. The study investigated the effect of sonic energy on the removal rate of the contaminants. The sonic generator used was a whistle which was believed to reach an intensity of 160 dB at the source. The experiments were performed by alternating between using sonic energy and not using sonic energy with the concentration and removal rate of the contaminants being observed. The results indicate that the use of sonic energy produced a 37.9% increase in the removal rate with a 95% confidence range of 30.96 to 44.89 percent and a 20.8% increase in the concentration of trichloroethylene with a 95% confidence range of 11.14 to 30.55 percent. These experiments showed that when sonic energy is coupled with pneumatic fracturing and vapor extraction in a site clean-up project, the removal rate of the volatile organic contaminants is increased considerably and the remediation time is correspondingly reduced. Further recommendations were made to investigate the decay of the sonic intensity in the fractures and to find the corresponding attenuation coefficients in the soil, which this current research effort is endeavoring to achieve.

CHAPTER 3

SITE DESCRIPTION

3.1 Background

The field studies will be carried out at the Derelco site, at Hillsborough, N.J., which is contaminated with trichloroethylene (TCE) and dichloroethylene (DCE). The site in which the contaminants had been discharged, had previously been investigated by McLaren/Hart Environmental Engineering. On October 26 1985, a fire destroyed a National Diagnostics Inc. building, located on the site and, thereafter, the site was no longer used. Presently, the site consists of 15 remediation bore wells most of which are 3.5" to 4" in diameter. The pertinent data for the various wells is listed in Table 3.1.

The site is located south of the Somerville traffic circle, on Route 206. It is a flat, partly paved site and generally slopes slightly from the Northwest towards the Southwestern direction. The surrounding area is a light industrial area and a tributary of the Royce Brook River runs eastward by the northern border of the site. Also located close to the site, about 100 feet, are a few medium sized building structures, (Boland et al, Ultrasonic Field Demonstration Work Plan, NJIT, 1998).

3.2 Site Geology

The geology of the Derelco Site is described by McLaren/Hart as "underlain by a thin veneer of unconsolidated sediments overlaying shale and siltstone bedrock." The deposits range in thickness from one to three feet. These deposits are believed to derive from the local bedrock and consist primarily of a heterogeneous mixture of silt and clay.

Rock samples by McLaren/Hart in September of 1990 revealed "a reddish brown siltstone with interbedded shale layers" and bedrock of "fair quality" with moderate fracture spacing: 30 centimeters to 1 meter apart. This study by McLaren/Hart also revealed three highly fractured zones within the bedrock. These zones appeared at a depth of 18 feet and at the intervals of 33 to 35 and 64 to 66 feet. Smaller fractures were also encountered at 29 feet, 40 feet, 55 feet, and 75 feet. Fractures are oriented both vertically and horizontally. Horizontal fractures occurred along bedding planes that dip five to ten degrees to the west. The vertical fractures are planar and parallel to the strike of the formation which, run Northwest to Southwest, (Boland et al, Ultrasonic Field Demonstration Work Plan, NJIT, 1998).

3.3 Site Hydrology

Previous investigations of the Derelco Site by McLaren/Hart Environmental Engineering revealed that the ground water circulation at the site occurred at a depth of about thirty feet below the ground level and the circulation is limited to the fractures located in this region. The studies also showed that the ground water circulated towards the Northeastern direction, (Boland et al, Ultrasonic Field Demonstration Work Plan, NJIT, 1998).

3.4 Well Layout

The locations of the wells within the site are depicted in Figure 3.1. Measured data for the wells at the Derelco site, Hillsborough Township, N.J, previously measured, are given in Table 3.1 and Table 3.2.

Table 3.1 Measured Data, Derelco Site Hillsborough Township, New Jersey

Well Number	X(ft)	Y(ft)	Depth(ft)	Conc. of TCE (PPMv)	Bore-hole size (inch)	Well Depth (ft)
1	53.3	25.6	26.80	1.8		85.00
2	47.9	19.7	7.00	30.0		19.10
3	58.1	20.0	6.90	13.2		17.55
4	36.5	19.2	7.90	59.5	4.0	21.65
5	30.5	31.1	8.42	13.0		21.22
6	23.9	30.1	8.49	6.8		24.27
7	24.7	22.3	8.32	7.6	4.0	22.16
8 fw	29.5	21.0	8.30	11.5	3.5	20.50
9	10.6	26.5	9.04	14.3		22.90
10	19.9	23.6	8.90	3.6		22.02
11	23.9	16.3	8.40	7.5	4.0	22.04
12	28.2	15.3	8.32	7.9		15.10
13	33.2	14.2	8.32	13.8	4.0	22.08
14	27.9	10.4	7.90	8.7		24.86
15	25.9	0.0	7.60	8.5		20.76

(Source: Boland et al, Ultrasonic Field Demonstration Work Plan, NJIT, 1998)

Table 3.2 Well Water Sample Analyses, Derelco Site Hillsborough Township, NJ.

Well Number	TCE, PPMv	DCE, PPMv
1		
2		
3		
4	23.14	4.66
5	19.98	2.32
6		
7	0.02	0.01
8	4.60	2.90
9	1.11	0.70
10	0.02	0.011
11	0.0	0.52
12	0.29	0.17
13	2.14	1.38
14	0.59	0.61
15		

(Source: Boland et al, Ultrasonic Field Demonstration Work Plan, NJIT, 1998)

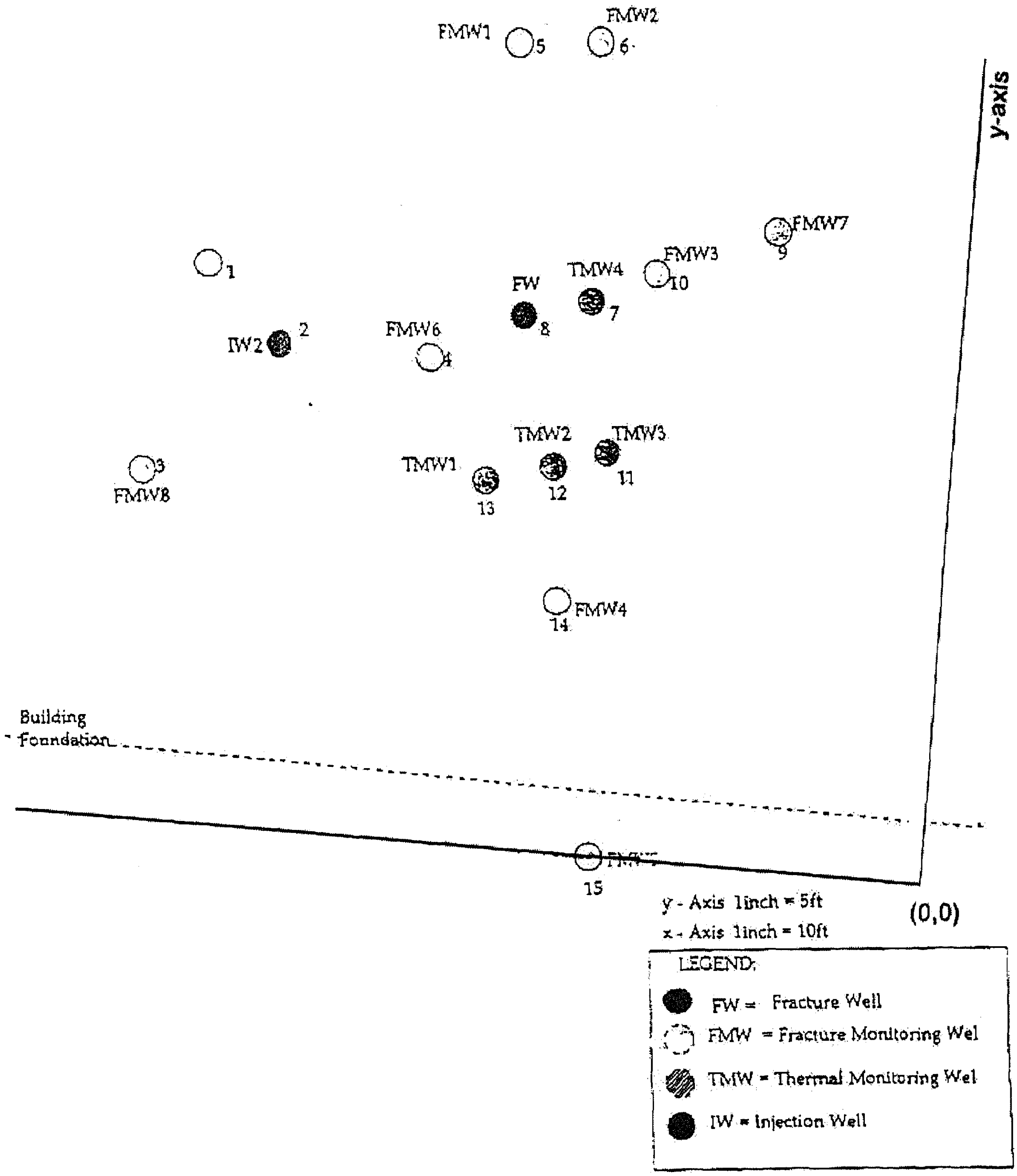


Figure 3.1 Approximate Location of Wells at the Derelco Site, Hillsborough Township, New Jersey (Refer Table 3.1), (Kaleem, 1999)

CHAPTER 4

UTILITIES AND EQUIPMENT SPECIFICATION

The equipment specification used for this research has been divided into four sections according to the experimental runs performed:

1. Equipment used for Preliminary Laboratory Test 1
2. Equipment used for Preliminary Laboratory Test 2
3. Equipment used for Field Experimental Runs
4. Equipment used for Field Experimental Runs to Specifically Record Base Values.

Some of the equipment used was the same between the individual sections and will be referenced to the earlier section when used again.

4.1 Equipment used for Preliminary Laboratory Test 1

This test was performed with Gary Elko at Lucent Technologies, Murray Hill, New Jersey so some of the equipment was specific to the laboratory in which the experiments were performed. The experimental setup is shown in Figure 4.1 and Figures C.9 – C.12.

4.1.1 Compressor

The compressor used in this case supplied air to all the labs in the building and was capable of providing a maximum air pressure of 100 psi in the laboratory and an air flowrate of a maximum of 7.5 scfm. This value was the maximum flowrate used in the tests. The compressor was needed to provide the air flowrate needed to produce the sonic energy by the whistle.

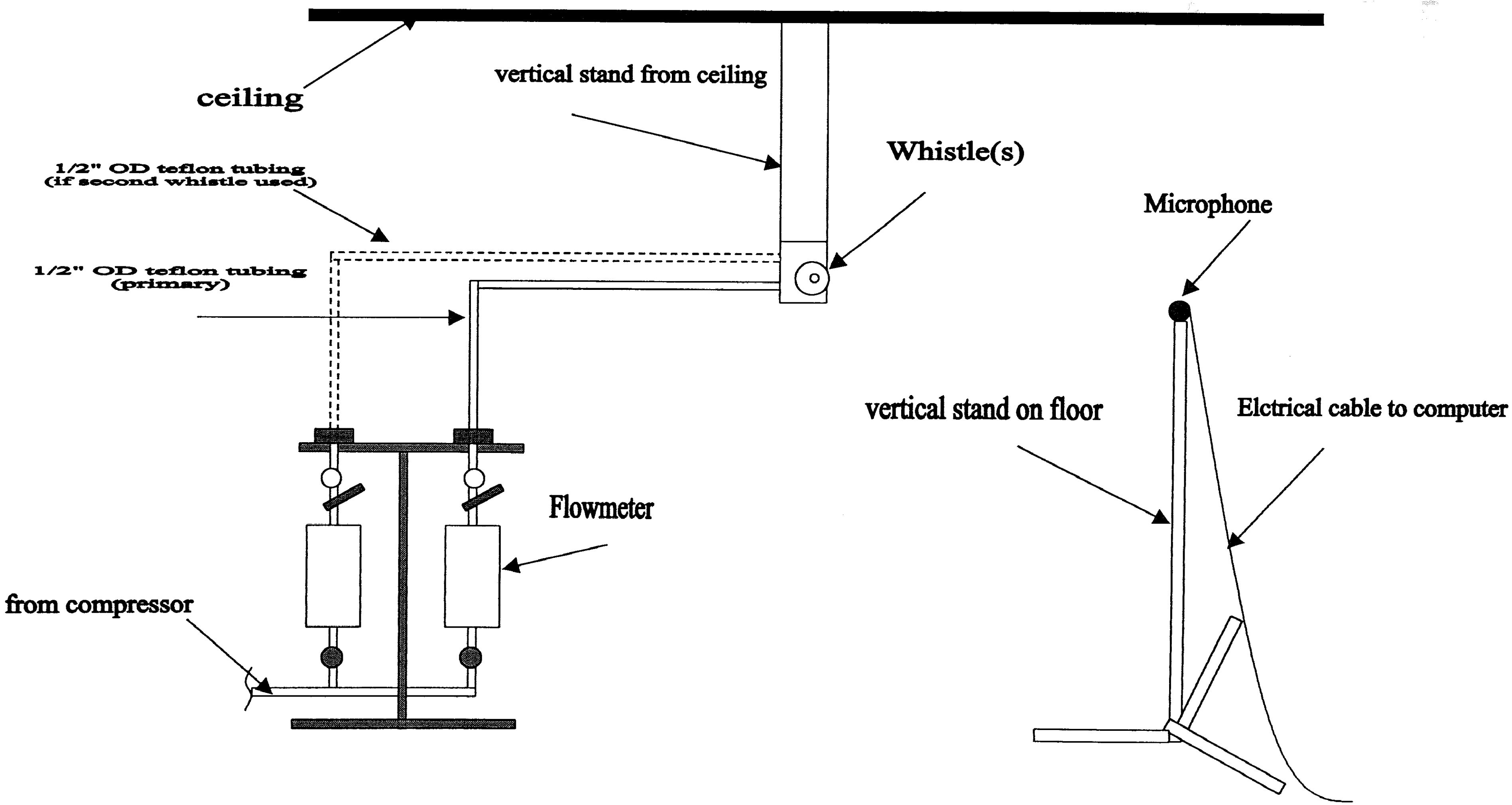


Figure 4.1 Test 1 – Choice of whistle

4.1.2 Flowmeters

Two identical flowmeters were used where each flowmeter has a ¾" ID with a flow measuring range of 2.0 - 24.0 SCFM. Each was equipped with a ½" Sch. 40 Bronze Globe valve at the inlet and a ½" Sch. 40 IPS Forged-Brass Ball valve at the outlet to regulate the air flowing through it. Each flowmeter was equipped with a 1/8" ID, 0-100 psi pressure gauge at its outlet to indicate the pressure drop through the whistle and its feed line. The inlet line to the flowmeter was connected to the compressor. The outlet of the flowmeter was connected to the whistle using ½" OD teflon tubing through a ½" OD ½" pipe size nylon compression tube on the flowmeter end and a ½" OD brass compression fitting on the whistle end. For the case where two whistles were used together, both flowmeters were used; otherwise, only one flowmeter was used.

4.1.3 Sonic Generator - Whistle

Five identical whistles were available for this experiment and each was tested to find the whistle that was most suitable for the experiments. They were purchased from Applied Ultrasonics, Bethel, Connecticut. Each whistle (Figure C.7) is about 3 inches long and is protected by two aluminum plates (Figure C.8) to protect the whistle from scraping along the wall of the bore-hole. Each whistle is unidirectional or faces a single direction and hence is capable of focusing the sonic energy into the fractures. In the experimental run, the whistle was supported by a vertical stand suspended from the ceiling at an arbitrary height. Each whistle is stated to have an intensity of 160 dB at the source by the manufacturer; however, the preliminary tests have shown that all the whistles do not have the same source intensity but the whistle with the highest source intensity, Whistle

Number 5, has a value that is very close to this stated value. Figure C.8 is a detailed schematic showing the whistle and the aluminum plates.

4.1.4 Microphone Assembly

The microphone and its related sound recording equipment were supplied by Lucent Technologies for the use of this study. The microphone used was a Bruel and Kjaer Type 4134, ½ inch, pressure condenser microphone. The microphone has a dynamic intensity measuring range of 21 to 160 dB with a 2639/69 preamplifier and a frequency range of 4 kHz to 20 kHz. The computer that was used to collect the signals was a 450 MHz Pentium II Hewlett Packard machine. The machine had a DSP – Siglab Box, Model No. 20 – 22, developed by DSP Technologies, which acted as the Data Acquisition Unit to which the microphone was plugged. The Siglab Box used the Siglab software, developed again by DSP Technologies, to produce what is called the Power Software Analyzer Virtual Instrument. This equipment, along with the microphone, worked as the sound measuring and recording instrument in this set of experiments. The microphone was supported on a vertical stand resting on the floor. It was aligned with the whistle at the same height.

4.2 Equipment used for Preliminary Laboratory Test 2

4.2.1 Compressor

The compressor was used to provide the air flow needed by the whistle to produce the sonic energy. The compressor used was a 1991 NAT'L. BD make compressor with an Maximum Available Working Pressure (MAWP) of 200 psi at 450°F and is capable of providing the required flowrate of upto 7 scfm. It is provided with a 0 - 200 psi pressure gauge to check the working pressure. The compressor outlet was fitted with a ½" female quick connect.

4.2.2 Flowmeter

The same flowmeter as that used in Section 4.1.2 was used for this test. However, the inlet of the flowmeter was fitted with a ½" female quick connect which was connected to the outlet of the compressor through a 25-foot nylon air-hose, ½" OD fitted with ½" male quick connects on both ends. The outlet of the flowmeter was fitted with a 3/8 inch compression fitting which connected to a 15-foot long, ½" OD Teflon tubing. This tubing further connected to the feed inlet to the whistle. The flowmeter was used to regulate the flow through the whistle, which in turn produced a change in sound intensity generated by the whistle.

4.2.3 Sonic Generator - Whistle

Out of the five available whistles, on the basis of the preliminary laboratory Test 1, Whistle Number 5 was used to generate the sonic energy needed for Test 2. The whistle referred to henceforth in the chapter, is this whistle, Whistle Number 5. The specifications for the whistle are the same as in Section 4.1.3. The whistle has a source intensity of 150 – 160 dB at a frequency of 11 kHz. The whistle was suspended by means of a vertical tripod stand at an arbitrary height from the ground. The whistle was connected to the flowmeter by means of a ½" OD Teflon tubing.

4.2.4 Microphone Assembly

A schematic diagram of the microphone assembly with the laptop is shown in Figure 4.2. The microphone assembly, Model No. ER-7C, is a clinical probe microphone system manufactured by Etymotic Research. It consists of a 3 inch soft silicone rubber probe with a six foot cord and a small preamplifier box with built-in equalization and 94 dB calibrator. The probe tube has a 0.95 mm OD, 0.5 mm ID and is 76 mm long (approximately 3 inch). An additional 40-foot audio cable was used along with the six-foot cord provided, to allow for comfortable working length. An audio cable 30 feet long was used to connect the preamplifier box to the line inlet of the laptop. The microphone can be calibrated using the built-in calibrator, which generates an intensity of 94 dB at 1 kHz. The microphone gives an undistorted output of 126 dB SPL in the "0 dB" position and 140 dB in the "-20 dB" position. It has a noise level of 55dB in the 20 to 20000 Hz bandwidth.

4.2.4.1 Calibration: This was done by inserting the microphone filament into the calibration hole provided on the top right hand corner of the preamplifier box and keeping the "on/off" switch depressed. The reading was read off the scale on the wave analyzer software installed on the laptop. This was a negative axis scale with units in decibels starting from zero as shown in Figure B.3. The reading obtained was a relative value and has a negative value corresponding to the 94 dB calibration tone. This relative value was added to the calibration tone 94 dB to get the reading corresponding to zero on the scale. This was then the calibration value. Any sound intensity measurement taken was read off the software scale and was added to this calibration value (since the relative value is taken off a negative axis scale) to get the absolute value in decibels. The calibration process is shown in Figures B.2 – B.4 and the process of calculating readings is shown in Figures B.5 – B.7.

4.2.5 Laptop

The laptop used was a Dell Latitude Xpi P133ST with a sound card, which was a minimum requirement in this study. The specifications of the laptop used included a 133 MHz processor, a 540 MB hard drive, 16 MB RAM memory and a sound card. The wave analyzer software Cool Edit 96 was installed on it to examine the wave recorded by the microphone.

4.2.6 Wave Analyzer Software - Cool Edit 96

Cool Edit 96 is a digital audio editor for Windows 95 and Windows NT. This software was the last component of the intensity measurement system used. It is an editor, recorder and player of sound. For this research, it analyses the sound wave and can display the frequency variation and the average intensity of the sound wave recorded. Figure B.1 – B.7 provides snapshots of sample screens obtained while analyzing the sound wave. The minimum system requirements for this software are:

- Windows 95/98 or Windows NT
- 486 or better CPU
- 8 MB RAM (32 recommended)
- 4 MB free hard disc space
- Stereo sound card

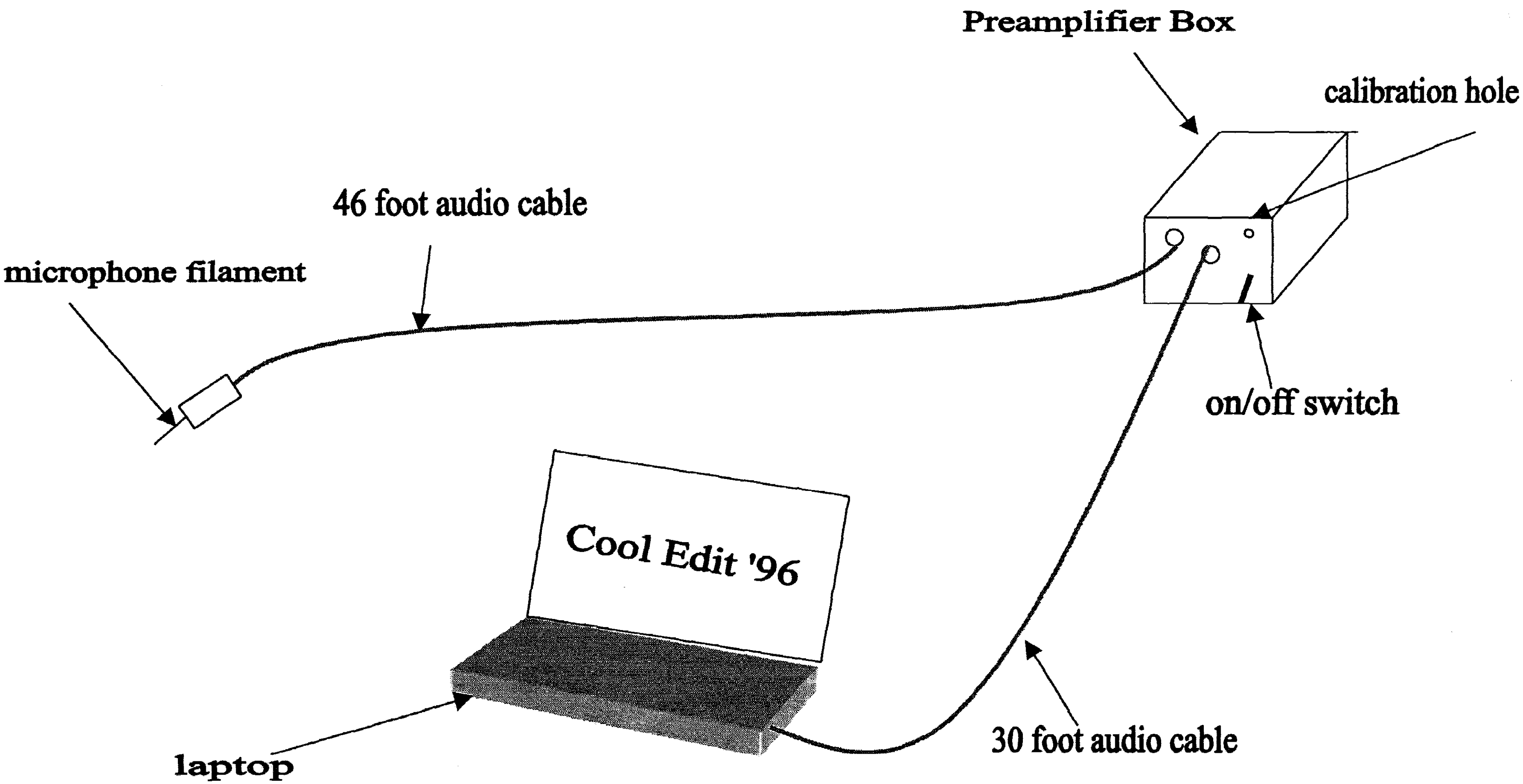


Figure 4.2 Microphone and its associated system.

4.3 Equipment used for Field Experimental Runs

4.3.1 Compressor

The compressor provided the air flow needed to produce the sonic energy generated by the whistle. The sonic energy and intensity of the whistle depends on the air flow through it. The compressor used for the experiments was a 1992 Ingersoll-Rand Industrial Air compressor Model No. T301080H with a Maximum Available Working Pressure (MAWP) of 200 psi at 450°F capable of providing the desired flowrates (upto 10 SCFM). By means of a bleed valve located underneath the compressor, all condensation can be bled out of the compressor. It is provided with a 0 - 200 psi pressure gauge to check the working pressure. An ARO valve, with a maximum pressure rating of 150 psi, at the discharge of the compressor, was used to regulate the flow through the flowmeter and to attain the desired outlet airflow rate.

4.3.2 Electronic Flowmeter

The electronic flowmeter was used to measure the air flow to the whistle. Since the intensity of the whistle is in direct proportion to the air flow to the whistle, the air flow was adjusted to provide the maximum intensity based on the results of the preliminary laboratory study. The flowmeter, Model 565-9-TA-AT, has been manufactured by Kurz™ Instruments, Inc. and falls into their DC-Powered Mass Flow Meters category. It is 1 inch by 12 inches in dimension and has a range of 0 - 50 scfm. It is ideally used for monitoring relatively clean air or gas flows. It gives a linearised 0 - 5 V DC signal representing the measured mass flow. This is converted into flow units scfm and displayed by a display box.

The outlet of the compressor was connected to the flowmeter by means of a ½" ID and 0.75" OD Braid-reinforced PVC tubing 130 feet long. This tubing was connected to the compressor through a 3/4" OD ½" pipe size polypropylene compression tube fitting and was connected to the flowmeter through a 1" Sch. 40 coupling and a 3/4" OD, ½" pipe size polypropylene compression tube fitting. The electronic flowmeter was kept to charge for approximately 1 hour on the day of the experimental run before using it in the experiment.

4.3.3 Sonic Generator - Whistle

Whistle Number 5 was used to generate the sonic energy needed for the experimental run. The specifications are the same as that mentioned in Section 4.1.3. The outlet of the flowmeter was connected to the whistle by means of a ½" OD Teflon tubing 35 feet long. This tubing was connected to the flowmeter through a 1" Sch. 40 coupling and a ½" OD, ½" pipe size nylon compression tube fitting, and was connected to the whistle through a ½" OD brass compression fitting.

4.3.4 Injection Well Setup

The injection well setup is shown in Figure C.1. The setup consisted of two 10-foot, 1" Sch. 40 PVS pipes connected by means of a 1" male adapter glued onto one of the pipes and a 1" female adapter glued onto the other pipe. The whistle was attached to one of the ends of the combined pipe by means of a 1" male adapter connected to one of the free ends of the combined pipe. A centering device was attached just above the whistle on the pipe, which was used to center the whistle in the well and to prevent damage to the whistle. The centering device consists of three equal lengths of spring steel, each approximately 8 inches long, which were bent in the form of an arc and fixed approximately 120° apart on the pipe by means of two 1" hose clamps. This setup supported the whistle in the well and carried the ½" OD Teflon tubing which supplied air flow from the flowmeter to the whistle. A steel vertical pipe riser clamp was used to hold the combined pipes at the top of the well. The pipes were marked at various intervals to indicate the direction of the mouth of the whistle. The pipes were also marked at intervals of 1 feet starting from the mouth of the whistle to facilitate the positioning of the whistle at the mouth of the fracture.

4.3.5 Extraction Well Setup

This extraction well setup is shown in Figure C.2. The setup consisted of two 10-foot, ½" Sch. 40 PVS pipes connected by means of a ½" male adapter glued onto one of the pipes and a ½" female adapter glued onto the other pipe. The microphone was fixed to one of the ends of the combined pipe by a small plastic tube that coupled the microphone to the pipe. A similar centering device as the one mentioned above was attached at the microphone end on the pipe, which was used to center the microphone in the well and to prevent damage to the microphone. A steel vertical pipe riser clamp was used to hold the combined pipes at the top of the well. A spring clamp was used in place of one of the nut-and-bolt sets to allow for quick clamping and unclamping of the pipes. The extraction pipes were marked at intervals of 1 feet from the tip of the microphone element to enable the positioning of the microphone at the various depths where the intensity is to be measured. This setup supported the microphone in the well and carried the audio cable, which supplied the signal from the microphone to the laptop.

4.3.6 Microphone Assembly with Laptop and Wave Analyzer Software

This system is exactly the same as that shown in Figure 4.1 and described in Sections 4.2.4, 4.2.5 and 4.2.6. The laptop was kept in the trailer to shelter it from the direct rays of the sun. This system was used to measure the sound intensity sensed by the microphone.

4.3.7 Sound Meter

A sound meter was used to verify the accuracy of the microphone assembly and its associated system. It is an Integrating impulse Sound Level Meter Type 2225 which displays the intensity in decibels on an analog scale. The measuring range of the meter is 25 dB to 140 dB in 4 display ranges: 20 - 60 dB, 50 - 90 dB, 80 - 120 dB and 100 - 120 dB. The microphone with the meter was ½" B & K condensor microphone Type 4175. The meter is shown in Figure C.10.

4.4 Equipment used for the Field Experimental Runs to Specifically Record Base Values

4.4.1 Compressor

The same compressor as that described in Section 4.3.1 was used to generate the air flowrate needed for the whistle to produce the sonic energy.

4.4.2 Electronic Flowmeter

The same electronic flowmeter as that described in Section 4.3.2 was used to regulate the air flowrate to the whistle and to the fracture. However, the outlet of the flowmeter in this case was fitted with a 1" Sch. 40 'Y'. Each end of the 'Y' was fitted with a 1" – ½" PVC reducer which was then further connected to a ½" Sch. 40, brass ball valve. One of the valves was fitted with a ½" OD, ½" pipe size compression fitting, male adapter which connected to the ½" OD Teflon tubing leading to the whistle. This allowed flow through the whistle. The other valve was fitted with a ½" Sch. 40 female quick connect which connected to a 25 foot nylon air-hose ½" OD with ½" male quick connects on both ends, with the other end connecting to the ½" female quick connect on the 'Y' on the extraction setup. This flow by-passed the whistle and provided air flow through the fracture.

4.4.3 Sonic Generator - Whistle

Once again, whistle Number 5 was used in the experiments to generate the sonic energy needed for the experiment. The specifications for the whistle are the same as that mentioned in Section 4.1.3.

4.4.4 Injection Well Setup

The injection well setup consists of a 1½" Sch. 40 'Y', three 4-foot, 1½" Sch. 40 steel pipes, and a 4-foot and a 2-foot packer. To one arm of the 1½" Sch. 40 'Y' was connected, through a reducer, a ½" female quick connect which connected to the ½" OD nylon air-hose connecting to the flowmeter to provide the whistle by-pass flow. The other arm of the 'Y' had a pipe adapter through which the ½" Teflon tubing passed and provided air flow to the whistle. The three 4-foot, 1½" Sch. 40 steel pipes were used as extension pipes and were connected to each other by means of 1½" Sch. 40 couplings. The lower end of the 'Y' was connected to one end of the pipes through a 1½" Sch. 40 union. This is shown in Figure C.3. The other end was then connected to the packer system, which consisted of the 4-foot and 2-foot packer with the whistle in between them (shown in Figure C.4), by using a 1½" nipple. The packers were used to isolate and prevent air-leakage from the fracture zone. The packers had an external tubing through which an external nitrogen cylinder can be used to inflate them. This setup carried the ½" OD Teflon tubing from the 'Y' to the whistle to provide air flow through the whistle. The whistle could be simply by-passed by using the valves on the flowmeter and air was then blown through this injection setup through the fractures. A steel vertical pipe riser clamp was used to hold the combined pipes at the top of the well. The pipes were marked at various intervals to indicate the direction of the mouth of the whistle. The pipes were also marked at intervals of 1 feet starting from the mouth of the whistle to facilitate the positioning of the whistle at the mouth of the fracture.

4.4.5 Extraction Well Setup

The extraction well setup consists of three 4-foot, 1¼" Sch. 40 steel pipes, and a 4-foot packer. The three 4-foot, 1¼" Sch. 40 steel pipes were used as extension pipes and were connected to each other by means of 1¼" Sch. 40 couplings. This is shown in Figure C.5. One end of the combined pipe was then connected through a 1¼" nipple to a 4-foot packer. This system was used to carry the microphone audio cables and to suspend the microphone from the open end of the packer. This is shown in Figure C.6. The packer was used to isolate and insulate the microphone from the ambient noise. The packer had an external tubing through which an external nitrogen cylinder could be used to inflate them. A steel vertical pipe riser clamp was used to hold the combined pipes at the top of the well. The pipes were also marked at intervals of 1 feet starting from the mouth of the whistle to facilitate the positioning of the microphone.

4.4.6 Microphone Assembly with Laptop and Wave Analyzer Software

This is the same as that described in Sections 4.2.4, 4.2.5 and 4.2.6. The microphone assembly was used to measure the intensity of the sound in the extraction well.

CHAPTER 5

EXPERIMENTAL APPROACH AND RESULTS

This research study consists of the following:

1. Preliminary Laboratory Experiments
2. Site Dewatering
3. Field Experimental Studies

5.1 Preliminary Laboratory Experiments

These laboratory tests which measured the attenuation of the sound in air were done prior to commencement of the field study. The first test was conducted at an acoustically insulated chamber at Lucent Technologies, Murray Hill, New Jersey with Gary Elko, to evaluate the effectiveness (in terms of intensity) of 5 whistles, which were manufactured by Applied Ultrasonics, Bethel, Connecticut and were available for the field study. One of the whistles was then chosen based on the highest intensity obtained at the mouth of the whistle at a given flow rate. A second study, conducted at the NJIT laboratory, was performed by comparing the intensity of the sound generated by the whistle chosen as measured by the computer software and by an analog sound meter used in previous research work. This was done to check and ensure the accuracy of the microphone and its associated system.

5.1.1 Test 1 – Choice of Whistle

This study was performed at Lucent Technologies, Murray Hill, New Jersey in their acoustics chamber. This chamber is a sound insulated chamber used for acoustic experiments. The setup for this test is described in Section 4.1 and shown in Figure 4.1 and Figures C.9 – C.12.

The tests were performed by varying the air flowrate using the flowmeter in steps of 0.5 scfm from 2 scfm to 6.5 – 7.0 scfm, the maximum possible with the available equipment, and keeping the distance of the microphone fixed at 100 cm from the whistle. This varying flowrate produced a change in intensity of the sound generated by the whistle, which was sensed by the microphone and measured by the software present on the computer. This reading was then recorded. The pressure at the output of the flowmeter, which reflected the pressure to the whistle, was also recorded. Tests were then performed on whistle numbers 5 and 4, the two best whistles (explained in the next section), to evaluate the sound intensity at varying distances from 0 to 150 cm and for various flowrates ranging from 4.5 scfm to 7.5 scfm.

5.1.1.1 Results of Test 1: The readings obtained were correlated in Figures A.1 – A.5. These graphs show the change in intensity of sound with change in air flow at a constant distance of 100 cm and for a particular whistle. These graphs show that Whistle Number 5 is the most effective whistle by producing an intensity of around 125 dB at 100 cm and at a flowrate of 6.0 scfm while the other whistles have a lower intensity at the same flowrate or at any other flowrate at the same distance. Whistle 4 is the next best whistle. Figure A.6 shows the effect on sound intensity with the two best whistles used together.

The sound intensity as a function of flowrate at a distance of 100 cm was less than that for Whistle Number 5. Figures A.7 – A.13 show the results of the variation of sound intensity with distance for varying flowrates for Whistle Number 4 and Figures A.14 – A.18 show these results for Whistle Number 5. Figures A.19 – A.21 show these results for the combination of whistle numbers 4 and 5. Figures A.22 – A.26 show the pressure at the outlet of the flowmeter versus flowrate for each whistle. These graphs show that Whistle Number 5 is most effective at a flowrate in the range of 6.0 – 6.5 scfm, and by extrapolating the curve to the y-axis the source intensity is found to be in the range of 150 – 160 dB. For Whistle Number 4, the next best whistle, at a flowrate in the range of 7 to 7.5 scfm, the source intensity was in the range of 125 – 145 dB. With the facts developed in Test 1, Whistle Number 5 alone was chosen for the field study.

5.1.2 Test 2 - Accuracy of the Intensity Measuring Equipment

This study was performed at the NJIT laboratory to ensure the accuracy of the microphone and its associated system consisting of the software program Cool Edit 96, the laptop, the preamplifier box, and the electrical cables. These tests were performed using whistle 5 based on the results of test 1. The experimental setup is described in Section 4.2. The microphone system was set up as shown in Figure 4.2.

The tests were performed by holding the microphone and the sound meter together (to ensure that the measuring conditions are the same) and measuring the change in intensity while the distance between the sound measuring devices and the whistle was changed, keeping the flowrate constant. The distances chosen were 25 cm, 50 cm, 75 cm, 100 cm, 150 cm and 300 cm. In each case three different sets of readings (R1, R2, R3) were taken. This procedure was repeated for flowrates of 6.5 scfm, 4.5 scfm and 3.5 scfm and again 6.5 scfm.

5.1.2.1 Results of Test 2: The readings obtained are shown in Figures A.27 - A.34. These graphs show the change in sound intensity with change in distance at a constant flow rate. These graphs are plotted at all the flowrates chosen for both the sound meter and the microphone. These tests show the consistency between each of the three readings of the microphone system and the sound meter and the consistency in the readings obtained by the sound meter and the microphone. This is more clearly shown by Figures A.35 - A.38 which show the comparison between the average values of the three readings taken by the sound meter and that of the microphone. The two curves follow each other closely. It can be concluded that the results obtained with the sound meter study and the results obtained with the intensity measuring equipment consisting of the microphone assembly, the laptop and the wave analyzer software are quite accurate and consistent. Hence the microphone system is suitable for the proposed field study with Whistle Number 5 giving the highest intensity at a flowrate of 6.5 scfm.

5.2 Site Dewatering

Prior to conducting the field experiments, the site was first dewatered to lower the water level below that of the fracture zone and to keep it there. This is necessary to ensure that no water is present in the fracture zone during the experiments so as to allow unobstructed flow of air through the fracture.

The process of dewatering basically involves pumping the water out of the well into a drum and from the drum to a large tank where it is temporarily stored. The well pump is a positive displacement pump while the pump in the drum is a float operated pump which starts pumping when the float is above the horizontal position depending on the water level in the drum. The pump in the drum is generally kept in automatic position to pump the water out of the well at regular intervals of time. This can be switched to manual operation for intensive dewatering. On initial manual operation, as soon as the water is pumped out of the well, the water rises quickly but as the aggressive dewatering continues, the rise in water level decreases until it almost remains at the pumped-down level. The water that is stored in the large tank is regularly treated at an on-site treatment facility after which it is recirculated into the local drainage system. Details are also given by Kaleem (1999). The Derelco site had been dewatered on automatic operation for more than a month prior to conducting the experimental runs and then for at least 1 day on manual operation prior to each set of experimental runs. This process ensured that the water level was always below the fracture zone during the experimental runs.

5.3 Field Experimental Studies

The purpose of this research is to determine the decay rate of sonic intensity used as an enhancement to the current technology of pneumatic fracturing and vapor extraction to aid in the removal of volatile organic contaminants present in tightly packed soils. These tests were conducted at the Derelco Industrial site located at Hillsborough, New Jersey, which is contaminated with trichloroethylene and dichloroethylene.

The approach was to pass sonic energy through a fracture between a pair of bore-wells and record the drop in intensity of the sonic wave as it propagates through the fracture between the wells. One well was used as the injection well where the whistle, supported by a 1" PVC pipe, generated the sonic energy required at the mouth of the fracture. The other well was used as the measuring well where the sound intensity was measured using a microphone, supported by a ½" PVC pipe, at the exit of the fracture. Since the intensity at the source was already known in proportion to the flowrate from the preliminary laboratory experiments, the drop in intensity can be calculated for the distance measured between the two wells. Based on this, the decay rate and the attenuation coefficient can be calculated. This procedure was repeated for various pairs of wells at different fracture heights.

The approach used was to pass sound through the fracture by generating sound using the whistle at the injection well and measuring the intensity using the microphone at the extraction well.

5.3.1 Experimental Setup for Field Runs

The experimental setup is described in Section 4.3 and is shown in Figure 5.1 and Figures C.13 – C.18.

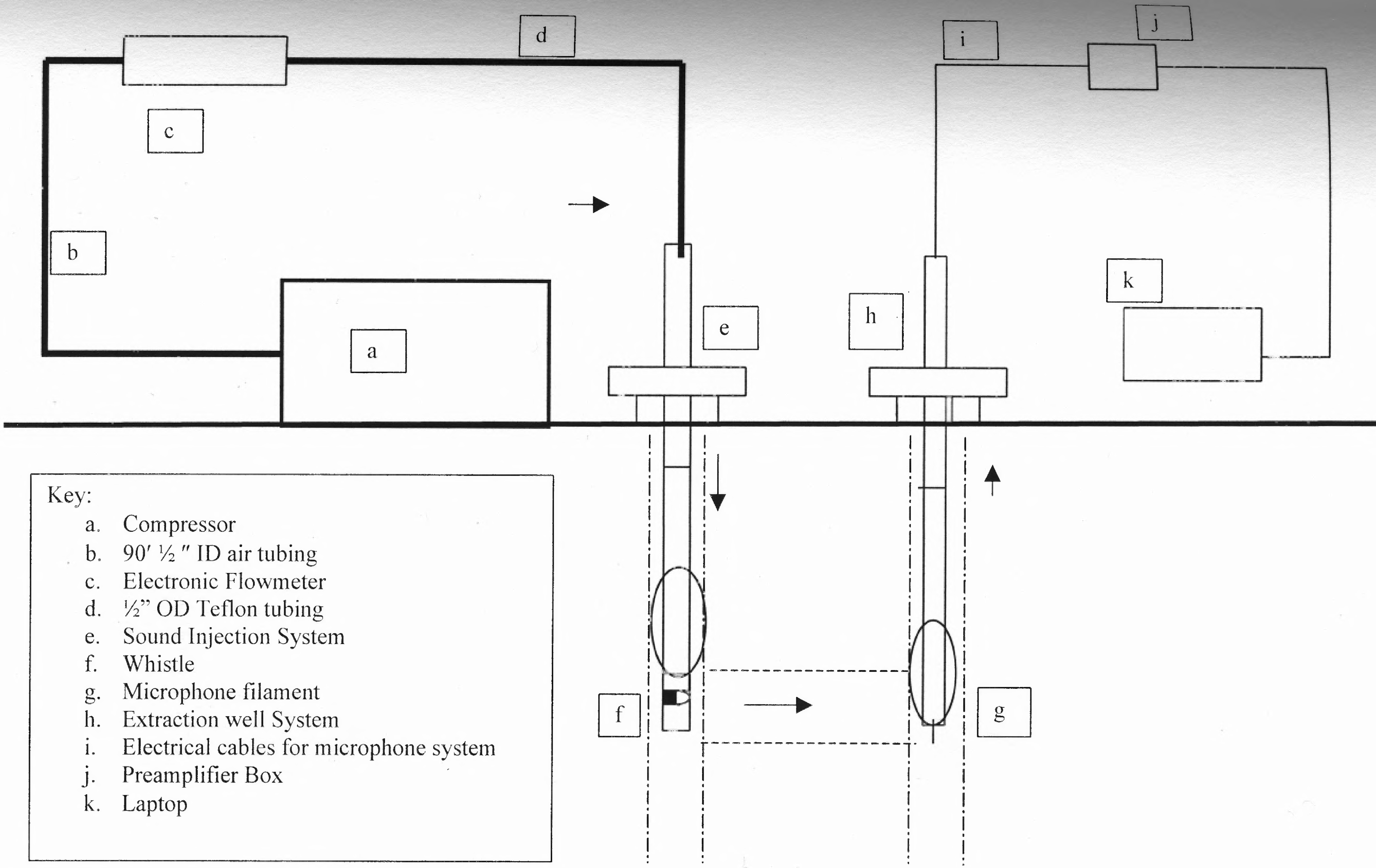


Figure 5.1 Field Experimental Setup

5.3.2 Experimental Procedure for Field Runs

The general experimental procedure was kept the same for each of the runs with any changes mentioned in the individual runs. This is shown in Figure 5.2 where the single black dot in the well (Well 4) represents the point at which sound was inserted into the fracture and the multiple black dots (Well 13) represent the points at which the sound intensity was measured.

The procedure involved the following: Before starting the experimental run, the microphone system with the Cool Edit software has to be calibrated as shown in Section 4.2.4.1. The calibration reading was recorded. The equipment was then assembled according to the experimental setup given in Section 4.3 and shown in Figure 5.1. The injection pipe assembly was then positioned using the clamp at the fracture height depending on the experimental run. The extraction pipe assembly was then positioned using the clamp initially at a depth approximately 1 foot above the water level in the well. The compressor was turned on with the flow valve off and was allowed to charge until it reached its maximum pressure of 140 psi. The valve was then opened and air was fed to the whistle. The electronic flowmeter measured the flowrate which was kept constant using the valve on the compressor. The "on/off" switch on the preamplifier box is then turned to "on". The sound wave at the microphone is then recorded using the laptop and the average value of the relative intensity of the recorded wave is obtained and noted down. The absolute value of the intensity is noted down by adding this value to the calibration value. The first reading was taken at the initial position of the microphone and each subsequent reading was taken by raising the microphone to the next fracture height or by a distance of 0.5 or 1 feet. This procedure is repeated for different fracture heights in the injection well between different sets of injection and extraction wells. The fracture heights for the whistle location in the injection wells and the microphone location in the extraction wells were chosen after viewing borehole videos taken of each of the relevant wells.

The experimental study involved 8 runs (Table 5.1) taken on various dates:

Experimental Run 1, 2, 3, 4: Sunday October 3, 1999

Experimental Run 5, 6: Friday October 8, 1999

Experimental Run 7, 8: Tuesday October 12, 1999

The results obtained are presented here and the discussion of the results is given in Chapter 6.

Table 5.1 Summary of Experimental Runs 1 - 8

Run	Injection Well	Extraction Well	Whistle depth (Feet BGS)	Distance between Wells (Feet)	Air Flowrate (scfm)
1	4	8	13.3	7.7	6.5
2	4	13	13.3	6.35	6.3
3	4	13	10.6	6.35	6.2
4	4	8	11	7.7	6.5
5	7	8	13.4	5.7	6.5
6	7	8	11.75	5.7	6.5
7	7	10	11.7	4.6	6.5
8	7	10	13.3	4.6	6.5

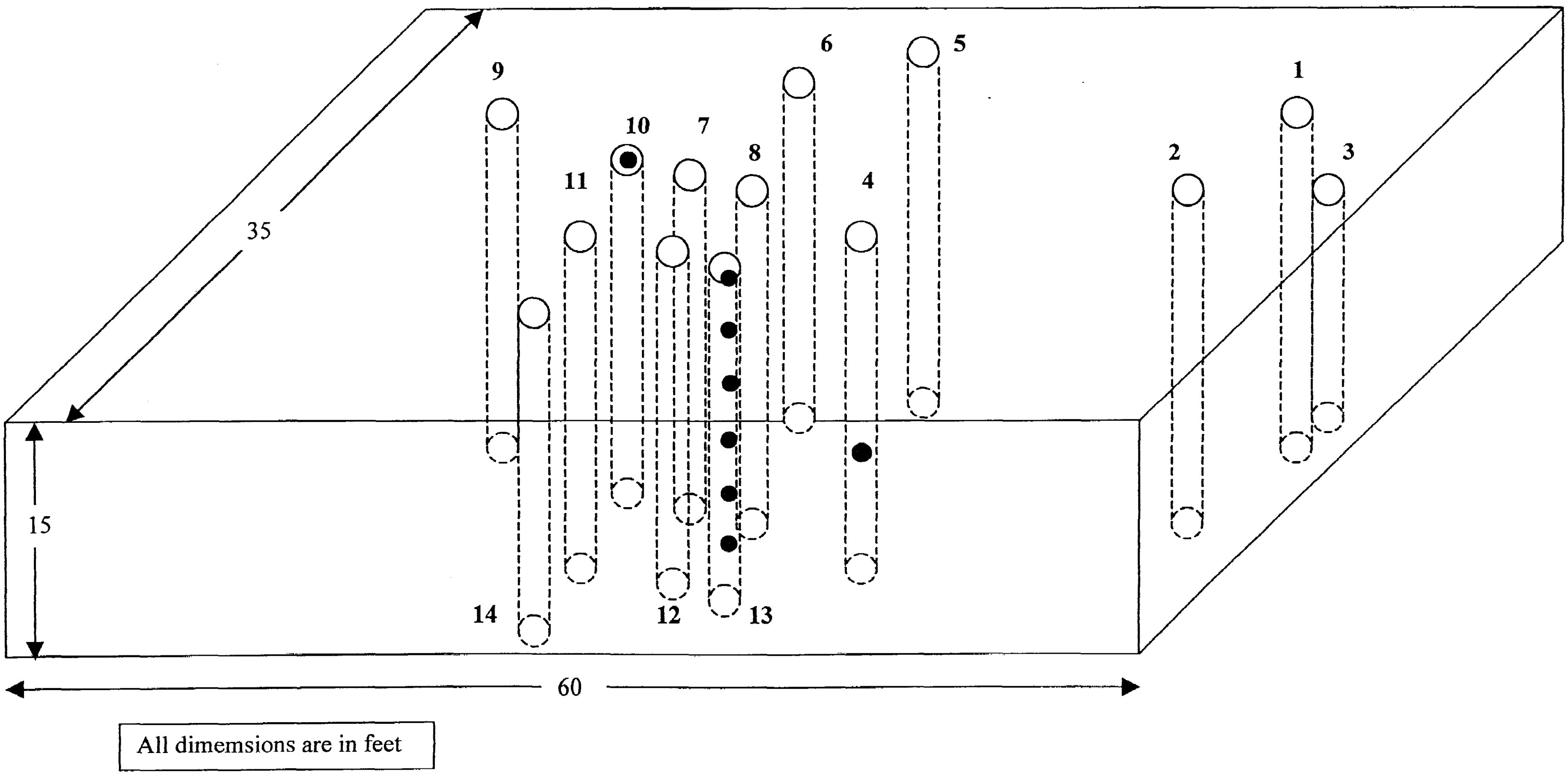


Figure 5.2 3-dimensional diagram demonstrating the experimental method used.

5.3.2.1 Experimental Run 1, Sunday October 3, 1999: This was the first run carried out. Well number 4 was chosen as the injection well and well number 8 was chosen as the extraction well. The distance between these wells was 7.7 feet. A fracture depth of 13.3 feet below ground surface (BGS) was chosen for the location of the whistle in the injection well. These conditions were chosen to simulate the same experimental conditions as Kaleem (1999) in which he obtained a 37.9% increase in the removal rate of the contaminants with a 95% confidence range of 30.96 to 44.89 percent. The flowrate was maintained at 6.5 scfm. The various microphone locations where the intensity was measured were 14.9 ft, 14.6 ft, 14.1 ft, 13.6 ft, 13.1 ft, 12.6 ft, 12.1 ft, 11.6 ft, 11.3 ft, 10.6 ft and 10.1 ft; all depths measured were from the ground surface. The results are shown in Table 5.2.

5.3.2.2 Experimental Run 2, Sunday October 3, 1999: Well number 4 was chosen as the injection well and well number 13 was chosen as the extraction well. The distance between these wells was 6.35 feet. A fracture depth of 13.3 feet BGS was chosen again for the location of the whistle in the injection well. The flowrate was maintained at 6.3 scfm. The various microphone locations where the intensity was measured were 14.6 ft, 14.3 ft, 13.8 ft, 13.3 ft, 12.8 ft, 12.3 ft, 11.8 ft, 11.3 ft, 10.8 ft, 10.3 ft, 9.8 ft, 9.3 ft and 8.8 ft; all depths measured were from the ground surface. The results are shown in Table 5.3.

5.3.2.3 Experimental Run 3, Sunday October 3, 1999: Well numbers 4 and 13 were again chosen as the injection well and the extraction well respectively. The distance between these wells was 6.35 feet. In this run, a fracture depth of 11 feet BGS was

Table 5.2 Results of Run 1

Injection well: 4

Extraction well: 8

Whistle depth: 13.3 ft BGS

Distance between the wells: 7.7 ft

Air Flowrate: 6.5 scfm

Microphone Depth (ft)	Intensity Reading 1 (dB)	Intensity Reading 2 (dB)	Intensity Reading 3 (dB)	Average (dB)
14.9	66.27	67.49	68.36	67.37
14.6	65.13	65.78	67.81	66.24
14.1	68.35	67.56	65.55	67.15
13.6	66.72	67.41	66.25	66.79
13.1	66.54	67.32	69.16	67.67
12.6	68.75	66.38	65.41	66.85
12.1	66.62	67.73	68.5	67.56
11.6	67.12	69.17	66.88	68.36
11.3	66.73	68.35	70.62	68.57
10.6	65.42	65.67	67.47	66.19
10.1	65.12	67.82	67.52	66.82

Table 5.3 Results of Run 2

Injection well: 4

Extraction well: 13

Whistle depth: 13.3 ft BGS

Distance between the wells: 6.35 ft

Air Flowrate: 6.3 scfm

Microphone Depth (ft)	Intensity Reading 1 (dB)	Intensity Reading 2 (dB)	Intensity Reading 3 (dB)	Average (dB)
14.6	67.61	68.87	67.32	67.93
14.3	68.1	69.17	68.42	68.56
13.8	69.9	69.12	66.97	68.66
13.3	69.85	67.85	68.75	68.82
12.8	69.72	69.34	70.57	69.88
12.3	69.24	68.44	70.93	69.54
11.8	69.03	70.88	69.76	69.89
11.3	67.0	68.18	70.8	68.66
10.8	69.65	69.52	68.19	69.12
10.3	70.46	69.78	68.81	69.68
9.8	68.23	68.48	69.3	68.67
9.3	70.34	67.67	66.35	68.12
8.8	68.55	67.96	66.0	67.5

chosen for the location of the whistle in the injection well. The flowrate was maintained at 6.2 scfm. The various microphone locations where the intensity was measured were 14.6 ft, 13.8 ft, 13.3 ft, 12.8 ft, 12.3 ft, 11.8 ft, 11.3 ft, 10.8 ft, 10.3 ft, 9.8 ft, 9.3 ft and 8.8 ft; all depths measured were from the ground surface. The results are shown in Table 5.4.

5.3.2.4 Experimental Run 4, Sunday October 3, 1999: Well number 4 was once again kept as the injection well and well number 8 was chosen as the extraction well. The distance between these wells was 7.7 feet. A fracture depth of 11 feet BGS was chosen again for the location of the whistle in the injection well. The flowrate was maintained around 6.5 scfm. The various microphone locations where the intensity was measured were 14.9 ft, 14.3 ft, 14.1 ft, 13.9 ft, 13.3 ft, 13.1 ft, 12.2 ft, 11.6 ft, 11.3 ft, 11.1 ft, 10.8 ft and 10.5 ft; all depths measured were from the ground surface. The results are shown in Table 5.5.

5.3.2.5 Experimental Run 5, Friday October 8, 1999: In this run, well numbers 7 and 8 were chosen as the injection well and the extraction well respectively. The distance between these wells was 5.7 feet. A fracture depth of 13.4 feet BGS was chosen for the location of the whistle in the injection well. The flowrate was maintained at 6.5 scfm. The various microphone locations where the intensity was measured were 14.3 ft, 14.1 ft, 13.9 ft, 13.1 ft, 12.2 ft, 11.6 ft, 11.1 ft, 10.6 ft and 10.1 ft; all depths measured were from the ground surface. The results are shown in Table 5.6.

Table 5.4 Results of Run 3

Injection well: 4

Extraction well: 13

Whistle depth: 10.6 ft BGS

Distance between the wells: 6.35 ft

Air Flowrate: 6.2 scfm

Microphone Depth (ft)	**Intensity Reading 1 (dB)**	**Intensity Reading 2 (dB)**	**Intensity Reading 3 (dB)**	**Average (dB)**
14.6	69.93	68.41	68.42	68.92
13.8	67.68	69.96	66.7	68.11
13.3	66.75	67.99	67.67	67.47
12.8	70.28	66.86	67.75	68.3
12.3	66.31	66.12	66.48	66.3
11.8	70.4	67.55	67.17	68.37
11.3	66.05	68.49	66.75	67.1
10.8	68.19	66.7	69.08	67.99
10.3	66.01	67.09	67.1	66.73
9.8	65.84	66.41	66.15	66.13
9.3	67.0	68.56	68.01	67.86
8.8	66.06	66.32	65.92	66.1

Table 5.5 Results of Run 4

Injection well: 4

Extraction well: 8

Whistle depth: 11 ft BGS

Distance between the wells: 7.7 ft

Air Flowrate: 6.5 scfm

Microphone Depth (ft)	Intensity Reading 1 (dB)	Intensity Reading 2 (dB)	Intensity Reading 3 (dB)	Average (dB)
14.9	68.6	69.18	69.87	69.22
14.3	67.81	67.49	68.45	67.92
14.1	67.94	70.47	68.84	69.08
13.9	68.27	67.62	65.88	67.26
13.3	65.66	66.21	64.93	65.6
13.1	64.82	66.54	67.99	66.45
12.2	65.55	65.58	66.37	65.83
11.6	68.01	66.24	67.65	67.3
11.3	64.9	66.24	67.09	66.08
11.1	66.76	65.69	65.12	65.86
10.8	65.19	66.34	66.22	65.92
10.5	65.79	68.21	65.52	66.51

Table 5.6 Results of Run 5

Injection well: 7

Extraction well: 8

Whistle depth: 13.4 ft BGS

Distance between the wells: 5.7 ft

Air Flowrate: 6.5 scfm

Microphone Depth (ft)	Intensity Reading 1 (dB)	Intensity Reading 2 (dB)	Intensity Reading 3 (dB)	Average (dB)
14.3	66.58	69.59	67.36	67.84
14.1	64.43	72.28	65.37	67.36
13.9	66.28	69.02	64.77	66.69
13.1	66.74	64.59	62.54	64.62
12.2	67.1	65.9	64.28	65.76
11.6	67.61	66.64	67.84	67.36
11.1	68.92	67.22	67.94	68.03
10.6	67.75	68.68	68.67	67.64
10.1	64.93	66.24	67.82	66.33

5.3.2.6 Experimental Run 6, Friday October 8, 1999: In this run, well numbers 7 and 8 were again chosen as the injection well and the extraction well respectively. The distance between these wells was 5.7 feet. In this run, a fracture depth of 11.75 feet BGS was chosen for the location of the whistle in the injection well. The flowrate was maintained around 6.5 scfm. The various microphone locations where the intensity was measured were 12.2 ft, 11.6 ft, 11.3 ft, 11.1 ft and 10.1 ft; all depths measured were from the ground surface. The results are shown in Table 5.7.

5.3.2.7 Experimental Run 7, Tuesday October 12, 1999: In this run, well numbers 7 and 10 were chosen as the injection well and the extraction well respectively. The distance between these wells was 4.6 feet. In this run, a fracture depth of 11.7 feet BGS was chosen for the location of the whistle in the injection well. The flowrate was maintained around 6.5 scfm. A major change introduced in this run and the following run is that the open end of the injection well and the open end of the extraction well were acoustically plugged using absorbent pads. This was done because it was noticed that the ambient noise, which included the sound of the whistle emerging from the open end of the injection well and entering the open end of the extraction well (not sound through the fracture), the noise of the compressor and the movement of traffic (since the site is adjoining Route 206), affected the readings taken by the microphone. The various microphone locations where the intensity was measured were 14.6 ft, 13.6 ft, 12.6 ft, 11.6 ft, 10.6 ft and 9.6 ft; all depths measured were from the ground surface. The results are shown in Table 5.8.

Table 5.7 Results of Run 6

Injection well: 7

Extraction well: 8

Whistle depth: 11.75 ft BGS

Distance between the wells: 5.7 ft

Air Flowrate: 6.5 scfm

Microphone Depth (ft)	**Intensity Reading 1 (dB)**	**Intensity Reading 2 (dB)**	**Intensity Reading 3 (dB)**	**Average (dB)**
12.2	65.93	64.83	65.32	65.36
11.6	64.52	66.82	67.69	66.34
11.3	64.93	64.02	66.36	65.69
11.1	65.32	67.0	64.76	65.69
10.1	68.16	68.3	68.65	68.37

Table 5.8 Results of Run 7

Injection well: 7

Extraction well: 10

Whistle depth: 11.7 ft BGS

Distance between the wells: 4.6 ft

Air Flowrate: 6.5 scfm

Microphone Depth (ft)	**Intensity Reading 1 (dB)**	**Intensity Reading 2 (dB)**	**Intensity Reading 3 (dB)**	**Average (dB)**
14.6	61.97	60.12	60.57	61.22
13.6	59.57	62.41	61.83	61.27
12.6	58.95	61.52	60.23	60.23
11.6	59.23	62.7	58.55	59.95
10.6	59.2	59.01	57.79	58.67
9.6	61.46	59.84	59.32	60.21

5.3.2.8 Experimental Run 8, Tuesday October 12, 1999: In this run, well numbers 7 and 10 were again chosen as the injection well and the extraction well respectively. The distance between these wells was 4.6 feet. In this run, a fracture depth of 13.3 feet BGS was chosen for the location of the whistle in the injection well. The flowrate was maintained at 6.5 scfm. In this run too, the open end of the injection well and the open end of the extraction well were acoustically plugged using absorbent pads. The various microphone locations where the intensity was measured were 14.6 ft, 13.6 ft, 13.1 ft, 12.6 ft, 11.6 ft, 10.6 ft and 9.6 ft; all depths measured were from the ground surface. The results are shown in Table 5.9.

Table 5.9 Results of Run 8

Injection well: 7

Extraction well: 10

Whistle depth: 13.3 ft BGS

Distance between the wells: 4.6 ft

Air Flowrate: 6.5 scfm

Microphone Depth (ft)	Intensity Reading 1 (dB)	Intensity Reading 2 (dB)	Intensity Reading 3 (dB)	Average (dB)
14.6	60.87	60.92	61.95	61.25
13.6	58.22	58.07	59.01	58.43
13.1	58.56	58.48	59.15	58.73
12.6	59.44	58.83	60.41	59.56
11.6	61.19	58.02	58.63	59.28
10.6	59.66	58.77	59.93	59.45
9.6	58.26	60.03	58.07	58.79

5.3.3 Final Field Tests for Base Values

These tests were performed to obtain certain base values that were needed to provide a complete set of experimental values to assist in providing the final conclusions. This experimental setup is similar to that used by Kaleem, 1999 in his field study, with certain modifications made to suit the specific needs of this research. The experimental procedure is given in the following sections with the results of the tests being provided later in this chapter.

5.3.3.1 Experimental Setup: The experimental setup is described in Section 4.4 and shown in Figure 5.3. Hereafter, Valve 1 refers to the valve which by-passes the whistle and Valve 2 refers to the valve which supplies air flow to the whistle to generate the sonic energy.

5.3.3.2 Experimental Procedure: Base value readings under four different sets of conditions were recorded for each run. However, for some of the runs, additional readings were also recorded. These four sets of conditions under which the readings were recorded were:

1. Keeping the open end of the extraction well, with the microphone in it, unsealed with all the other systems off, which in other words was exposing the microphone to the ambient noise without any restrictions.

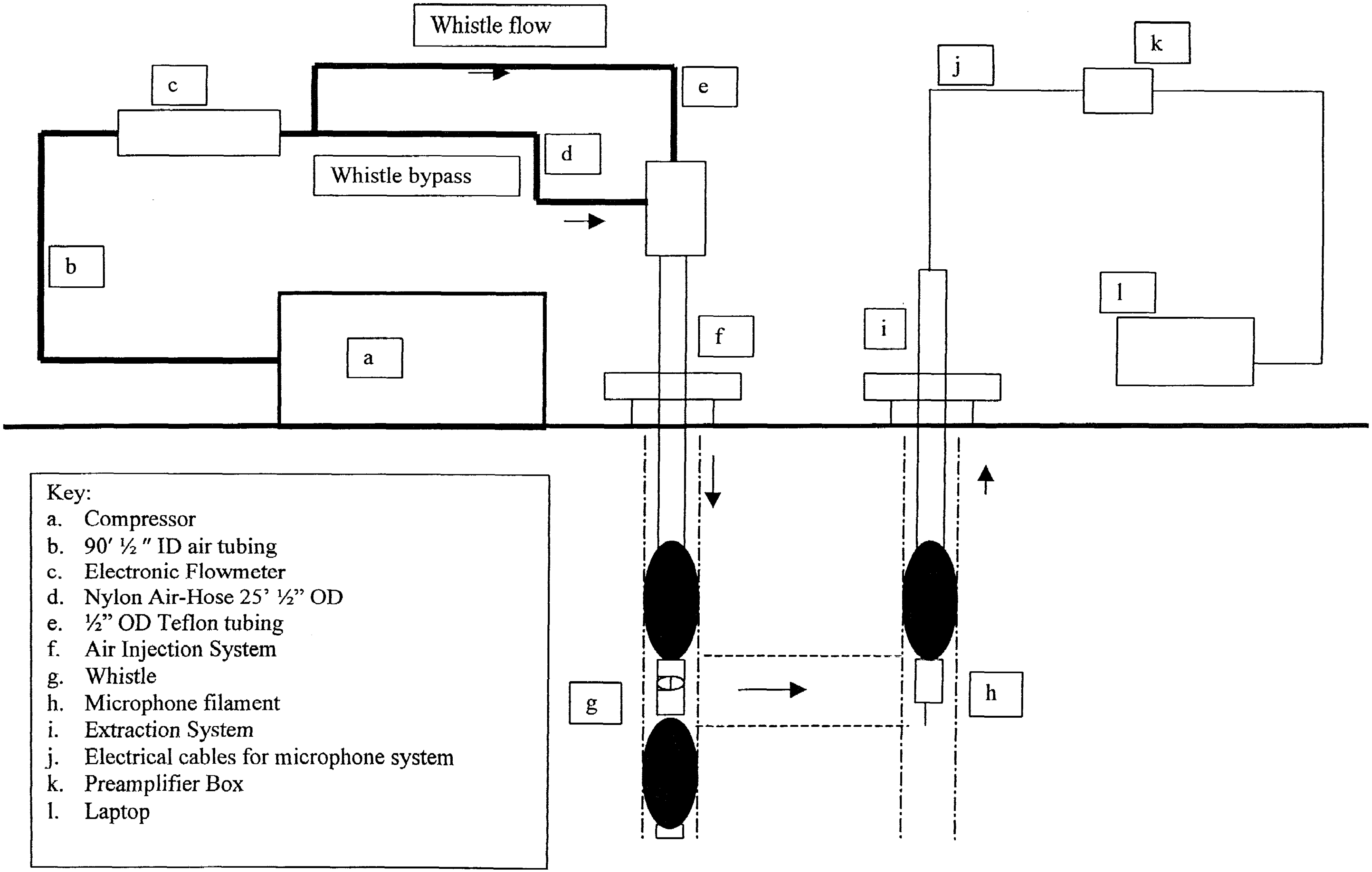


Figure 5.3 Field Experimental Setup for Measurement of Base Values

2. Sealing the open end of the extraction well with all the other systems off. The seal was provided by inflating the packers and by plugging the open end with absorbent pads. The microphone would measure only the sound it received in the well without the ambient noise affecting it.
3. Keeping the extraction well and hence the microphone sealed off and by opening Valve 1 and closing Valve 2, thus injecting only air which has bypassed the whistle through the fracture. This was done to check if the air alone in passing through the fracture created any sound, which would be picked up by the microphone. The air flowrate was maintained between 6.5 – 5.7 scfm.
4. In all the previous cases, the whistle was not turned on. In this case, keeping the extraction well sealed, the whistle was turned on by opening Valve 2 and closing Valve 1. This, of course, was done to check if the microphone recorded any sound intensity other than the ambient noise, which would imply that the sound recorded would probably be attenuated sound coming from the whistle. The flowrate of air through the whistle was maintained at 6.5 – 6.7 scfm.

This part of the study consisted of 5 experimental runs (Table 5.10) performed on:

Experimental Run 9, 10: Sunday November 7, 1999

Experimental Run 11, 12, 13: Sunday November 14, 1999

The results obtained are presented here and the discussion of the results is given in Chapter 6.

5.3.3.3 Experimental Run 9, Sunday November 7, 1999: This run was performed with well number 7 as the injection well and well number 10 as the extraction well. The distance between these wells was 4.6 feet. A fracture depth of 11.7 feet below ground surface was chosen for the location of the whistle while a depth of 11.6 feet was chosen for the microphone. Readings were also recorded for two more sets of conditions in addition to the four mentioned above in Section 5.3.3.2. In the first set of conditions, keeping the extraction well sealed and by opening Valve 1 and closing Valve 2, only air was passed through the fracture bypassing the whistle with no sound. This is the same as Condition 3 mentioned above except that the air flow was kept on for 45 minutes before taking the readings. The second set of readings is similar to Condition 4 mentioned above with the air passing through the whistle, by keeping Valve 1 closed and Valve 2 opened. The readings, however, are taken after exposing the fracture to the sound for 45 minutes. The results are given in Table 5.11.

Table 5.10 Summary of Experimental Runs 9 - 13

Run	Injection Well	Extraction Well	Whistle Depth	Microphone Depth	Distance between wells (feet)	Air Flowrate (scfm)
9	7	10	11.7	11.6	4.6	6.5 – 6.7
10	4	8	11.65	11.6	7.7	6.5 – 6.7
11	4	8	13.3	14.9	7.7	6.5 – 6.7
12	4	13	13.3	14.9	6.35	6.5 – 6.7
13	7	10	13.3	12.5	4.6	6.5 – 6.7

Table 5.11 Results of Run 9

Injection well: 7

Extraction well: 10

Whistle depth: 11.7 ft BGS

Microphone depth: 11.6 ft BGS

Distance between the wells: 4.6 ft

Air Flowrate: 6.5 – 6.7 scfm

Conditions	**Reading 1 (dB)**	**Reading 2 (dB)**	**Reading 3 (dB)**	**Average (dB)**
0. Initial Test – Table 5.8 Microphone sealed at 11.6 ft BGS	59.23	62.7	58.55	59.95
1. Microphone unsealed, all other systems OFF	65.13	68.7	63.36	65.73
2. Microphone sealed, all other systems OFF	59.92	62.34	63.04	61.77
3. Microphone sealed, air ON, Bypass whistle	59.95	62.38	62.37	61.2
4. Microphone sealed, air ON, Through whistle	62.97	61.71	61.76	62.15
5. Microphone sealed, air ON, Bypass whistle 45 minutes	62.22	61.66	61.82	61.9
6. Microphone sealed, air ON, Through whistle 45 minutes	62.32	63.5	62.42	62.75

5.3.3.4 Experimental Run 10, Sunday November 7, 1999: This run was performed with well number 4 as the injection well and well number 8 as the extraction well. The distance between these wells was 7.7 feet. A fracture depth of 11.65 feet below ground surface was chosen for the location of the whistle while a depth of 11.6 feet was chosen for the microphone. The results are given in Table 5.12.

5.3.3.5 Experimental Run 11, Friday, November 19, 1999: This run was performed with again well numbers 4 and 8 as the injection and extraction wells respectively. The distance between these wells was 7.7 feet. A fracture depth of 13.3 feet below ground surface was chosen for the location of the whistle while a depth of 14.9 feet below ground surface was chosen for the microphone. These conditions were the same as those chosen by Kaleem (Kaleem, 1997) in his experiments where he obtained a 37.9% increase in the removal rate of the contaminants with a 95% confidence range of 30.96 to 44.89 percent. Readings were also recorded for two more sets of conditions in addition to the four mentioned above in Section 5.3.3.2. In the first set of conditions, keeping the extraction well sealed, only air was passed through the fracture with no sound, by opening Valve 1 and closing Valve 2. This is the same as Condition 3 mentioned above except that the air flow was kept on for 45 minutes before taking the readings. The second set of readings is similar to Condition 4 mentioned above with only sound passed through the fracture and no air, by keeping Valve 1 closed and Valve 2 opened. The readings, however, are taken after exposing the fracture to the sound for 45 minutes. The results are given in Table 5.13.

Table 5.12 Results of Run 10

Injection well: 4

Extraction well: 8

Whistle depth: 11.65 ft BGS

Microphone depth: 11.6 ft BGS

Distance between the wells: 7.7 ft

Air Flowrate: 6.5 – 6.7 scfm

Conditions	**Reading 1 (dB)**	**Reading 2 (dB)**	**Reading 3 (dB)**	**Average (dB)**
0. Initial Test – Table 5.5 Microphone unsealed at 11.6 ft BGS	68.01	66.24	67.65	67.3
1. Microphone unsealed, all other systems OFF	64.01	61.26	62.77	62.68
2. Microphone sealed, all other systems OFF	59.77	59.25	59.57	59.53
3. Microphone sealed, air ON, Bypass whistle	69.4	69.01	69.26	69.23
4. Microphone sealed, air ON, Through whistle	70.3	69.35	70.62	70.1

Table 5.13 Results of Run 11

Injection well: 4

Extraction well: 8

Whistle depth: 13.3 ft BGS

Microphone depth: 14.9 ft BGS

Distance between the wells: 7.7 ft

Air Flowrate: 6.5 – 6.7 scfm

Conditions	Reading 1 (dB)	Reading 2 (dB)	Reading 3 (dB)	Average (dB)
0. Initial Test – Table 5.2 Microphone unsealed at 14.6 ft BGS	66.27	67.49	68.36	67.37
1. Microphone unsealed, all other systems OFF	67.44	64.74	67.28	66.49
2. Microphone sealed, all other systems OFF	61.95	62.0	62.23	62.06
3. Microphone sealed, air ON, Bypass whistle	78.15	78.89	78.71	78.58
4. Microphone sealed, air ON, Through whistle	71.96	72.02	72.77	72.25
5. Microphone sealed, air ON, Bypass whistle 45 minutes	80.5	78.58	79.25	79.44
6. Microphone sealed, air ON, Through whistle 45 minutes	70.8	69.98	69.62	70.13

5.3.3.6 Experimental Run 12, Friday November 19, 1999: This run was performed with well number 4 as the injection well and well number 13 as the extraction well. The distance between these wells was 6.35 feet. A fracture depth of 13.3 feet below ground surface, the same as the previous run, was chosen for the location of the whistle while a depth of 14.9 feet was chosen for the microphone, again the same as the previous run. The results are given in Table 5.14.

5.3.3.7 Experimental Run 13, Friday November 19, 1999: This run was performed with well number 7 as the injection well and well number 10 as the extraction well. The distance between these wells was 4.6 feet. A fracture depth of 13.3 feet below ground surface was chosen for the location of the whistle while a depth of 12.5 feet was chosen for the microphone. These locations were chosen since fractures were seen at this depth in the borehole videos taken. The results are given in Table 5.15.

5.3.4 Concluding test to check sound attenuation in air over a larger distance

The procedure and equipment used in this test were similar to that in Test 2, explained in Section 5.1.2, with the exception that the test was performed on-site and only one flowrate of 6.5 scfm was tested for. This test was performed using Whistle Numbers 4 and 5 to check the attenuation of sound in air over a distance of 600 cm. The results are shown in Figures A.39 and A.40 for Whistle Numbers 4 and 5 respectively.

Table 5.14 Results of Run 12

Injection well: 4

Extraction well: 13

Whistle depth: 13.3 ft BGS

Microphone depth: 14.9 ft BGS

Distance between the wells: 6.35 ft

Air Flowrate: 6.5 – 6.7 scfm

Conditions	**Reading 1 (dB)**	**Reading 2 (dB)**	**Reading 3 (dB)**	**Average (dB)**
0. Initial Test – Table 5.3 Microphone unsealed at 14.6 ft BGS	67.61	68.87	67.32	67.93
1. Microphone unsealed, all other systems OFF	66.82	66.21	67.73	66.92
2. Microphone sealed, all other systems OFF	67.24	66.92	67.09	67.08
3. Microphone sealed, air ON, Bypass whistle	67.25	67.02	66.67	66.98
4. Microphone sealed, air ON, Through whistle	66.76	67.25	68.01	67.34

Table 5.15 Results of Run 13

Injection well: 7

Extraction well: 10

Whistle depth: 13.3 ft BGS

Microphone depth: 12.5 ft BGS

Distance between the wells: 4.6 ft

Air Flowrate: 6.5 – 6.7 scfm

Conditions	Reading 1 (dB)	Reading 2 (dB)	Reading 3 (dB)	Average (dB)
0. Initial Test – Table 5.9 Microphone sealed at 12.6 ft BGS	59.44	58.83	60.41	59.56
1. Microphone unsealed, all other systems OFF	67.88	68.82	67.15	67.95
2. Microphone sealed, all other systems OFF	68.93	69.04	68.81	68.93
3. Microphone sealed, air ON, Bypass whistle	72.38	73.26	73.21	72.95
4. Microphone sealed, air ON, Through whistle	73.83	73	72.49	73.11

CHAPTER 6

DISCUSSION OF EXPERIMENTAL RESULTS

6.1 Experimental Run 1 and Run 11

The results of experimental Run 1 are presented in Table 5.1. Well numbers 4 and 8 were the injection and extraction wells respectively, with the whistle location at 13.3 ft below ground surface. The wells and the whistle location chosen were the same as that chosen by Kaleem (1999), in which he obtained a 37.9% increase in the removal rate of the contaminants with a 95% confidence range of 30.96 to 44.89 percent. The whistle location and the multiple locations of the microphone were chosen by viewing the borehole videos made of the wells. In Table 5.1, the readings were taken by applying sonic energy (keeping the whistles on) to the fractures. The average value of the readings obtained at the various depths of the microphone in the well tally quite closely with each other. However, the readings of the intensity obtained at the extraction well don't seem to be conclusive. This was because the intensity recorded did not seem to be due to the sound generated by the whistle but due to the ambient noise in the environment, which is in the same intensity range as that measured in Run 1. One of the factors accounting for the ambient noise was the presence of a road, Route 206, approximately 40 meters away from the site. The road had medium to heavy traffic plying on it most of the time. Another factor that could produce the ambient noise was the presence of the Derelco business center around the site, consisting mainly of warehouses and a few small offices. Most of the time, there was a low level of activity at the business center. The noise level of the preamplifier box and the sound card would also be a big factor since this value, which is around 55 dB, is significant. It would not be possible to measure an intensity lower than 55 dB for this reason. However, intensity lower than this value would be useless to this technology since the drying effect of the sound is most effective around 150 dB. To verify the effect of the ambient noise on the readings, the experimental setup was modified as explained in Section 5.3.3 and further experimental runs were performed, consisting of measuring base values for various conditions as those mentioned in Section 5.3.3.2.

Using the same conditions as those in Run 1, experimental Run 11 was performed with the microphone positioned at a constant depth of 14.9 ft BGS. The results of Run 11 are tabulated in Table 5.11. Condition 0 in Table 5.11 represents the intensity values obtained at a depth of 14.6 ft BGS of the microphone in Run 1 and are taken from Table 5.1. Condition 1 represents the condition when the microphone was kept unsealed with all other systems off, including the whistle, and readings were recorded under these conditions. The intensity readings obtained would be only due to the ambient noise in the surrounding. The average reading of the intensity obtained in condition 1 agrees very well with that in condition 0. This shows that the readings in Run 1 were probably due to the ambient noise and there is no definitive way to say that the intensities measured were due to the sound energy generated by the whistle. The next condition, condition 2, represented the state when the microphone was sealed with all other systems, including the whistle, off. This condition would provide readings that represented intensities of sound within the well, almost insulated from the ambient noise in the surroundings. The average value of the intensity obtained under this condition showed a drop of 4.5 dB from that in condition 1 which showed that the ambient noise was being cut-off to a certain extent. This residual sound read by the microphone is mostly due to the noise generated by the preamplifier box and the sound card of the laptop. However, since all readings would now be compared with those in condition 2 as the base value, this problem would be eliminated.

Condition 3 represents the state when the microphone was sealed and air was applied to the fracture keeping the sound off, i.e. the whistle off. Any excess intensity recorded by the microphone above that in condition 2 would be due to the sound generated by the air moving through the fracture and rushing against the microphone filament in the extraction well. The average value of the intensity obtained, 78.58, which is 16 dB above the value in condition 2, 62.06, could be due to this effect.

Condition 4 in Table 5.11 represents the condition when the microphone was sealed, by-pass air was switched off and only the sound generated by the air passing through the whistle was passed through the fracture. The average value of the intensity recorded by the microphone under these conditions, 72.25, is considerably larger than that in condition 2 but is 6 dB less than that in condition 3. Since it is lower than the intensity recorded in condition 3, all the sound generated by the whistle is absorbed by the rock around it and the fracture through which the sound passes. The sound recorded could be due to the air passing through the whistle which is used to generate the sound energy and then passing into the fracture. However, since this air is restricted by the whistle and is more focused, it probably generates less sound than the air in condition 3 due to which the intensity in condition 4 is lower than that in condition 3. One probable theory to explain this effect is given here. Fractures are highly irregular in nature and there is no way to predict their profile under the ground. Hence the length of the fracture could be very large as compared to the straight-line distance between the wells and the cross-sectional profile of the fracture is highly irregular under the ground. As given in the background study, Chapter 2, there are various factors, like divergence, reflection, refraction, diffraction, absorption, etc. due to which sound attenuates in a medium. There are also some specific factors that specially affect sound propagation in solids, like grain and domain boundary effects, interstitial atom diffusion, etc. One other important factor is the extreme absorption of sound in pores of very small radii, which is the case in fractures. Due to these effects, the sound generated by the whistle is absorbed in a local zone around the mouth (injection point) of the fracture. Due to this localized effect, the drying effect in this region is highly increased due to which the contaminants in this region get depleted. This sets up a concentration gradient of the contaminants between the local depleted region and the surrounding region. This causes the organic contaminants to diffuse into the depleted region. As the depletion and diffusion process goes on, the overall concentration of the contaminants in the surrounding soil decreases. This effect is more marked by using sound as compared to using just air according to the current technology, since the concentration gradient created by using the sound is much larger than the concentration gradient created by just the air due to which the overall concentration of the contaminated site decreases much faster using sound and hence, allows faster remediation and a lower remediation time.

Condition 5 and condition 6 in Table 5.11 are the same as condition 3 and condition 4 respectively except that each new test is performed for a duration of 45 minutes. These additional conditions were also checked to see if a longer duration of the air and sound application produced any additional effect as compared to that obtained by taking instant readings. However, the value of the average intensity obtained for condition 5 is very close to that obtained for condition 3 while the value obtained for condition 6 is very close to that obtained for condition 4. Hence, there is no significant change in the value of the intensities recorded by the microphone in the respective cases. A long-term application of the sound or the air does not have any effect on the intensity value recorded by the microphone.

6.2 Experimental Run 4 and Run 10

The results of experimental Run 4 are presented in Table 5.4. Well numbers 4 and 8 were again the injection and extraction wells respectively, with the whistle location this time at 11 ft below ground surface. The readings were taken by applying sonic energy (keeping the whistles on) to the fractures. The average value of the readings obtained at the various depths of the microphone in the well tally quite closely with each other, after taking into account some experimental error. However, the readings of the intensity obtained at the extraction well again don't seem to be conclusive. This was because the intensity recorded again did not seem to be due to the sound generated by the whistle but due to the ambient noise in the environment, which is in the same intensity range as that measured in Run 4. To verify the effect of the ambient noise on the readings, using the same conditions as those in Run 4 except that the whistle location was at 11.65 ft BGS, experimental Run 10 was performed with the microphone positioned at a constant depth of 11.6 ft BGS. The results of Run 10 are tabulated in Table 5.10. Condition 0 in Table 5.10 represents the intensity values obtained at this constant depth of the microphone in Run 4 and are taken from Table 5.4. Condition 1 represents the condition when the microphone was kept unsealed with all other systems off, including the whistle, and readings were recorded under these conditions. The intensity readings obtained would be only due to the ambient noise in the surrounding. There is a difference of 4.6 dB between the average reading of the intensity obtained in condition 1 and that in condition 0. This change is noticed because the ambient noise keeps on changing depending on the amount of activity in the surroundings. Hence, there was probably less surrounding activity during Run 10 than in Run 4. Another factor to look at is that the value of the average intensity in Table 5.4 vary with the different depths of the microphone but stay within the same range. The average value in condition 0 in Table 5.10 is on the higher side of this range and hence the difference between condition 0 and condition 1 is larger. In other words, due to experimental variation the readings vary within limits and so there could be a difference in the values of the readings in condition 0 and condition 1. Condition 2, represented the state when the microphone was sealed with all other systems off, including the whistle. This condition would provide readings that represented intensities of sound within the well, almost insulated from the ambient noise in the surroundings. The average value of the intensity obtained under this condition showed a drop of 3 dB from that in condition 1 which showed that the ambient noise was being cut-off to a certain extent. This residual sound read by the microphone is mostly due to the noise generated by the preamplifier box and the sound card of the laptop. However, since all readings would now be compared with those in condition 2 as the base value, this problem would be eliminated.

Condition 3 represents the state when the microphone was sealed and air was applied to the fracture keeping the sound off, i.e. the whistle off. Any excess intensity recorded by the microphone above that in condition 2 would be due to the sound generated by the air moving through the fracture and rushing against the microphone filament in the extraction well. The average value of the intensity obtained, 69.23, which is 10 dB above the value in condition 2, 59.53, could be due to this effect.

Condition 4 in Table 5.10 represents the condition when the microphone was sealed, air was switched off and only the sound generated by the air passing through the whistle was passed through the fracture. The average value of the intensity recorded by the microphone under these conditions, 70.1, is again 10.5 dB larger than that in condition 2 and is almost the same as that in condition 3. Again, it seems that all the sound generated by the whistle is absorbed by the rock around it and the fracture through which the sound passes. The same theory proposed in Section 6.1 can be applied here. The sound recorded could be due to the air passing through the whistle which is used to generate the sound energy and then passing into the fracture. However, due to the irregular nature of the fractures, this time, the value of the intensity readings in condition 4 are the same as that in condition 3.

6.3 Experimental Run 2, Run 3 and Run 12

The results of experimental Run 2 are presented in Table 5.2. Well numbers 4 and 13 were the injection and extraction wells respectively, with the whistle location at 13.3 ft below ground surface. The readings were taken by applying sonic energy (keeping the whistles on) to the fractures. The average value of the readings obtained at the various depths of the microphone in the well tally quite closely with each other. However, the readings of the intensity obtained at the extraction well again don't seem to be conclusive. This was because the intensity recorded again did not seem to be due to the sound generated by the whistle but due to the ambient noise in the environment, which is in the same intensity range as that measured in Run 2. This same effect was seen in Run 3, which was performed between the same sets of wells except that the whistle was at a depth of 10.6 ft. To verify the effect of the ambient noise on the readings, using the same conditions as those in Run 2, experimental Run 12 was performed with the microphone positioned at a constant depth of 14.9 ft BGS. The results of Run 12 are tabulated in Table 5.12. Condition 0 in Table 5.12 represents the intensity values obtained at a depth of 14.6 ft BGS of the microphone in Run 2 and are taken from Table 5.2. Condition 1 represents the condition when the microphone was kept unsealed with all other systems off, including the whistle, and readings were recorded under these conditions. The intensity readings obtained would be only due to the ambient noise in the surrounding. The average reading of the intensity obtained in condition 1 agrees very well with that in condition 0. This shows that the readings in Run 1 were probably due to the ambient noise and there is no definitive way to say that the intensities measured were due to the sound energy generated by the whistle. Condition 2, represented the state when the microphone was sealed with all other systems off, including the whistle. This condition would provide readings that represented intensities of sound within the well, almost insulated from the ambient noise in the surroundings. The average value of the intensity obtained under this condition remained the same as that in condition 1 which showed that the microphone was probably not well insulated by the packers and that the ambient noise was still affecting the readings. However, since all readings would now be compared with those in condition 2 as the base value, this problem would be eliminated.

Condition 3 represents the state when the microphone was sealed and air was applied to the fracture keeping the sound off, i.e. the whistle off. The average value of the intensity obtained was almost the same as that in condition 1 and condition 2. Thus, it seems that there was no air or sound reaching the extraction well due to which the microphone recorded only the ambient noise. This is probably because the fracture could be highly irregular and much longer so that it absorbed any sound generated by the air passing through the fracture. Condition 4 represents the condition when the microphone was sealed, air was switched off and only the sound generated by the air passing through the whistle was passed through the fracture. The average value of the intensity obtained was again almost the same as that in condition 1, condition 2 and condition 3. Again, it seems that all the sound generated by the whistle is absorbed by the rock around it and the fracture through which the sound passes. Hence, the microphone reads only the ambient noise in the surroundings again.

6.4 Experimental Run 7 and Run 9

The results of experimental run 7 are presented in Table 5.7. Well numbers 7 and 10 were used as the the injection and extraction wells respectively, with the whistle location at 11.7 ft below ground surface. The readings were taken by applying sonic energy (keeping the whistles on) to the fractures. However, in this run, the microphone was sealed by plugging the mouth of the injection and extraction wells with adsorbent pads. The average value of the readings obtained at the various depths of the microphone in the well tally quite closely with each other. However, the readings of the intensity obtained at the extraction well again don't seem to be conclusive. This was because the intensity recorded again did not seem to be due to the sound generated by the whistle but due to some noise in the environment, which is probably due to the noise in the preamplifier box and the sound card of the laptop. Since the microphone was already sealed, the ambient noise was being eliminated. To verify the effect of the noise on the readings, using the same conditions as those in Run 7, experimental Run 9 was performed with the microphone positioned at a constant depth of 11.6 ft BGS. The results of Run 9 are tabulated in Table 5.9. Condition 0 in Table 5.9 represents the intensity values obtained at this constant depth of the microphone in Run 7 and are taken from Table 5.7. Condition 1 represents the condition when the microphone was kept unsealed with all other systems off, including the whistle, and readings were recorded under these conditions. The intensity readings obtained would be only due to the ambient noise in the surrounding. Condition 2, represented the state when the microphone was sealed with all other systems off, including the whistle. This condition would provide readings that represented intensities of sound within the well, almost insulated from the ambient noise in the surroundings. The average value of the intensity obtained under this condition showed a drop of 4 dB from that in condition 1 which showed that the ambient noise was being eliminated to a certain extent. The average intensity value in condition 2 is close to that in condition 0, since in this run, they represent readings taken under the same conditions. This resident sound read by the microphone is mostly due to the noise generated by the preamplifier box and the sound card of the laptop. However, since all readings would now be compared with those in condition 2 as the base value, this problem would be eliminated.

Condition 3 represents the state when the microphone was sealed and air was applied to the fracture keeping the sound off, i.e. the whistle was off. The average value of the intensity obtained was almost the same as that in condition 2. Thus, it seems that there was no air or sound reaching the extraction well due to which the microphone recorded only noise in its sealed condition. This is probably because the fracture could be highly irregular and much longer so that it absorbed any sound generated by the air passing through the fractures. Condition 4 represents the condition when the microphone was sealed, air was switched off and only the sound generated by the air passing through the whistle was passed through the fracture. The average value of the intensity obtained was again almost the same as that in condition 2 and condition 3. Again, it seems that all the sound generated by the whistle is absorbed by the rock around it and the fracture through which the sound passes. Hence, the microphone reads only the noise due to the preamplifier box and the sound card of the laptop again.

Condition 5 and condition 6 in Table 5.9 are the same as condition 3 and condition 4 respectively except that each new test is performed for a duration of 45 minutes. These additional conditions were also checked to see if a longer duration of the air and sound application produced any additional effect as compared to that obtained by taking instant readings. However, the values of the average intensity obtained for condition 5 and condition 6 are very close to that obtained for condition 2 and condition 3. Hence, there is no significant change in the value of the intensities recorded by the microphone in the respective cases. A long-term application of the sound or the air does not have any effect on the intensity value recorded by the microphone.

6.5 Experimental Run 8 and Run 13

The results of experimental Run 8 are presented in Table 5.8. Well numbers 7 and 10 were again the injection and extraction wells respectively, with the whistle location this time at 13.3 ft below ground surface. The readings were taken by applying sonic energy (keeping the whistles on) to the fractures. However, in this run, the microphone was sealed by plugging the mouth of the injection and extraction wells with adsorbent pads. The average value of the readings obtained at the various depths of the microphone in the well tally quite closely with each other. However, the readings of the intensity obtained at the extraction well again don't seem to be conclusive. This was because the intensity recorded again did not seem to be due to the sound generated by the whistle but due to additional noise in the environment, which is in the same intensity range as that measured in Run 8. To verify the effect of the ambient noise on the readings, using the same conditions as those in Run 8, experimental Run 13 was performed with the microphone positioned at a constant depth of 12.5 ft BGS. The results of Run 13 are tabulated in Table 5.13. Condition 0 in Table 5.13 represents the intensity values obtained at a constant depth of 12.6 ft BGS of the microphone in Run 8 and are taken from Table 5.8. Condition 1 represents the condition when the microphone was kept unsealed with all other systems off, including the whistle, and readings were recorded under these conditions. The intensity readings obtained would be only due to the ambient noise in the surrounding. There is a difference of 7 dB between the average reading of the intensity obtained in condition 1 and that in condition 0. Condition 2, represented the state when the microphone was sealed with all other systems off, including the whistle. This condition would provide readings that represented intensities of sound within the well, almost insulated from the ambient noise in the surroundings. Some discrepancy was observed since the average value of the intensity obtained under this condition was the same as that in condition 1 which could be because the microphone was not sealed properly, due to which the ambient noise was not eliminated. However, since all readings would now be compared with those in condition 2 as the base value, this problem would be eliminated.

Condition 3 represents the state when the microphone was sealed and air was applied to the fracture keeping the sound off, i.e. the whistle off. The average value of the intensity obtained, 72.95, is 4 dB above the value in condition 2, 68.93. This is probably due to any sound generated by the air passing through the fracture or rushing against the microphone. Condition 4 represents the condition when the microphone was sealed, air was switched off and only the sound generated by the air passing through the whistle and then passing through the fracture was detected. The average value of the intensity recorded by the microphone under these conditions, 73.11, is almost the same as that in condition 3. Again, it seems that all the sound generated by the whistle is absorbed by the rock around it and the fracture through which the sound passes. The same theory proposed in Section 6.1 can be applied here. The sound recorded could be due to the air passing through the whistle which is used to generate the sound energy and then passing into the fracture.

6.6 Experimental Run 5 and Run 6

The results of experimental Runs 5 and 6 are presented in Tables 5.5 and 5.6 respectively. Well numbers 7 and 8 were used as the injection and extraction wells respectively, with the whistle location this time at 13.4 ft below ground surface for Run 5 and 11.75 ft BGS for Run 6. The readings were taken by applying sonic energy (keeping the whistles on) to the fractures. The average value of the readings obtained at the various depths of the microphone in the well tally quite closely with each other for each run. The average values of the intensity for both the runs are in the same range too. However, the readings of the intensity obtained at the extraction well again don't seem to be conclusive. This was because the intensity recorded again did not seem to be due to the sound generated by the whistle but due to additional noise in the environment, which is in the same intensity range as that measured in Runs 5 and 6. Further base tests were not performed.

6.7 Discussion of Concluding Test – Sound Attenuation over a Larger Distance

The results of the concluding test, performed to check the sound attenuation over a larger distance of 600 cm, are presented in Figure A.39 and A.40 for Whistle Numbers 4 and 5 respectively. These tests were performed to demonstrate the attenuation of sound in air over a distance of 600 cm, which was approximately 30 dB dropping from a source intensity of approximately 120 dB to 90 dB. In the soil fractures, there a lot of other factors (mentioned in Chapter 2) which absorb sound energy and hence the decay in soil will be much larger than in air. Hence, this only reiterates the point that the sound is being absorbed very quickly in the ground and the effect of the sound is only seen in a localized region as explained in Section 6.1. These results are compared with the results obtained in Test 1 taken under similar conditions but only up to a distance of 150 cm, which are shown in Figures A.11 and A.18 for Whistle Numbers 4 and 5. A comparison of Figure A.18 with Figure A.39, which were made at the same conditions but at a later date, shows that there is a drop of about 20 dB at the source for Whistle Number 4. Since the Run shown in Figure A.39 was made at a later date than the Run shown in Figure A.18, it may be possible that some erosion has occurred thus altering the sound intensity generated at the source. However, no visible signs of erosion were observed. In Test 2, while comparing the microphone to the sound meter, a similar reduction in sound intensity was obtained but only for Whistle Number 5 (Compare Figures A.35 and Figures A.38).

6.8 Factors Involved in the Study

Several factors have been observed which could affect the results to a considerable extent. These have been listed here:

1. The permeability of the fractures could drastically affect the sound propagation through the ground. In other words, the fractures being either "open" or "closed", would drastically affect the results too. However, in this research, the effect of this factor is probably negligible because permeability studies done by Kaleem (Kaleem, 1999) have shown that the permeability of the fractures has not been affected over the years and that the fractures are "open".
2. The quality of the whistle could degrade over a period of time due to erosion created by the air rushing past the converging mouth of the whistle at speeds almost equal to the speed of sound. Hence, the intensity at the source and along the various paths of the whistle would reduce and the whistle would not be as effective. However, no visible evidence of erosion was observed.

3. The location of the mouth of the fractures in the various wells has been recorded by viewing the borehole videos made of the wells. However, it is difficult to say whether any fracture would have better permeability as compared to any other fracture. Hence, the choice of the fracture chosen for the location of the whistle could also be a factor affecting the readings observed.
4. Again, since the location of the fractures have been recorded by viewing the borehole videos, there could be some uncertainty in the exact location of the fracture and in the positioning of the whistle at the mouth of the fracture also. Hence, the whistle may not be directly focused at the fracture.
5. Another factor that could affect the attenuation of sound in the fractures is the moisture content of the soil. This is known to absorb the sonic energy and increase the attenuation to a considerable extent. Since, there is also air in the voids in the soil and rock, this has an even greater effect in increasing attenuation (discussed in Chapter 2).
6. As seen above, the ambient noise has some effect on the readings observed. However, for the intensity required for this technology of sound application to be effective, the intensity should be around 150 dB. At this intensity level, the ambient noise should have a negligible effect. However, since the readings observed were around 60 – 70 dB, the ambient noise was a significant factor and showed that the sound generated by the whistle was absorbed in the fracture before it reached the microphone at the extraction well.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Most of the sonic energy produced by the whistle is absorbed by the rock around the fracture. In other words, there is a large amount of attenuation that takes place in the rock and soil present at the Derelco site. This attenuation is due to a large number of factors that are characteristic of the nature of the soil and rock present. Most of the sound energy is absorbed before it reaches the microphone or sound recording end. Hence, the microphone cannot distinguish between the sound it receives from the whistle and the ambient noise and reads only ambient noise.

However, it has been clearly shown by Kaleem (1999) that there is an improvement in the removal rate of the volatile organic compounds present in the contaminated site, by the application of Sonic Energy along with Pneumatic Fracturing and Vapor Extraction. One probable theory to explain this increase in the rate of removal when sonic energy is applied even though most of the energy is absorbed by the soil is that the effect of the sound or sonic energy is localized and most of the acoustic energy is absorbed in a localized region around the source of the sound. This means that the increased benefit of applying acoustic energy is realized only in a localized region, thereby lowering the concentration of the contaminants in that region. As a result of this the concentration gradient of the contaminants between the remediated region and the contaminated region increases, resulting in increased mass transfer between the two regions. This results in an overall increase in the concentration of the contaminants in the effluent air and hence an increase in the contaminant removal rate. A decrease in the remediation time taken to clean the site will result.

7.2 Recommendations

It is recommended that more tests should be made to investigate other parameters that may greatly affect the outcome of the results. One possible setup to determine these could be a laboratory simulation of the conditions at the site. This could involve making an artificial fracture between slabs of rock and placing pipes simulating boreholes on either end of the slabs with a sound generating source in one pipe and a sound measuring device in the other pipe, thus recreating the environment at the Derelco site. Factors affecting the propagation of sound and its attenuation through the fracture should then be investigated.

It is also recommended that whistles capable of generating a higher intensity level at the source should be experimented with, to see if there is an increase in the removal rate of the contaminants. Hence, optimum values of the power and intensity of the whistle could be obtained. Instead of a whistle, a multi-directional source like a siren with the capability to produce a frequency up to 20 kHz and an intensity greater than 160 dB could be designed and used and its effect on the removal rate and sound attenuation could be studied. Larger diameter boreholes at the Derelco site would be needed to accommodate the larger diameter siren. . It is, furthermore, recommended that controlled attenuation studies be made in a bed of soil with the microphone placed in boreholes at closer distances to the sound source. The larger fixed borehole distances at the Hillsborough site would not allow a quantitative indication of how rapidly the sound intensity decreased.

Also, the effect of other parameters that seem to affect the propagation of sound and air such as the orientation and location of the fractures can be studied. Eventually all these parameters can be built into a mathematical model to predict the expected amount of enhancement and the effective range of sonic field. These factors will enhance the design of future field decontamination studies.

APPENDIX A

DATA OF PRELIMINARY LABORATORY TESTS

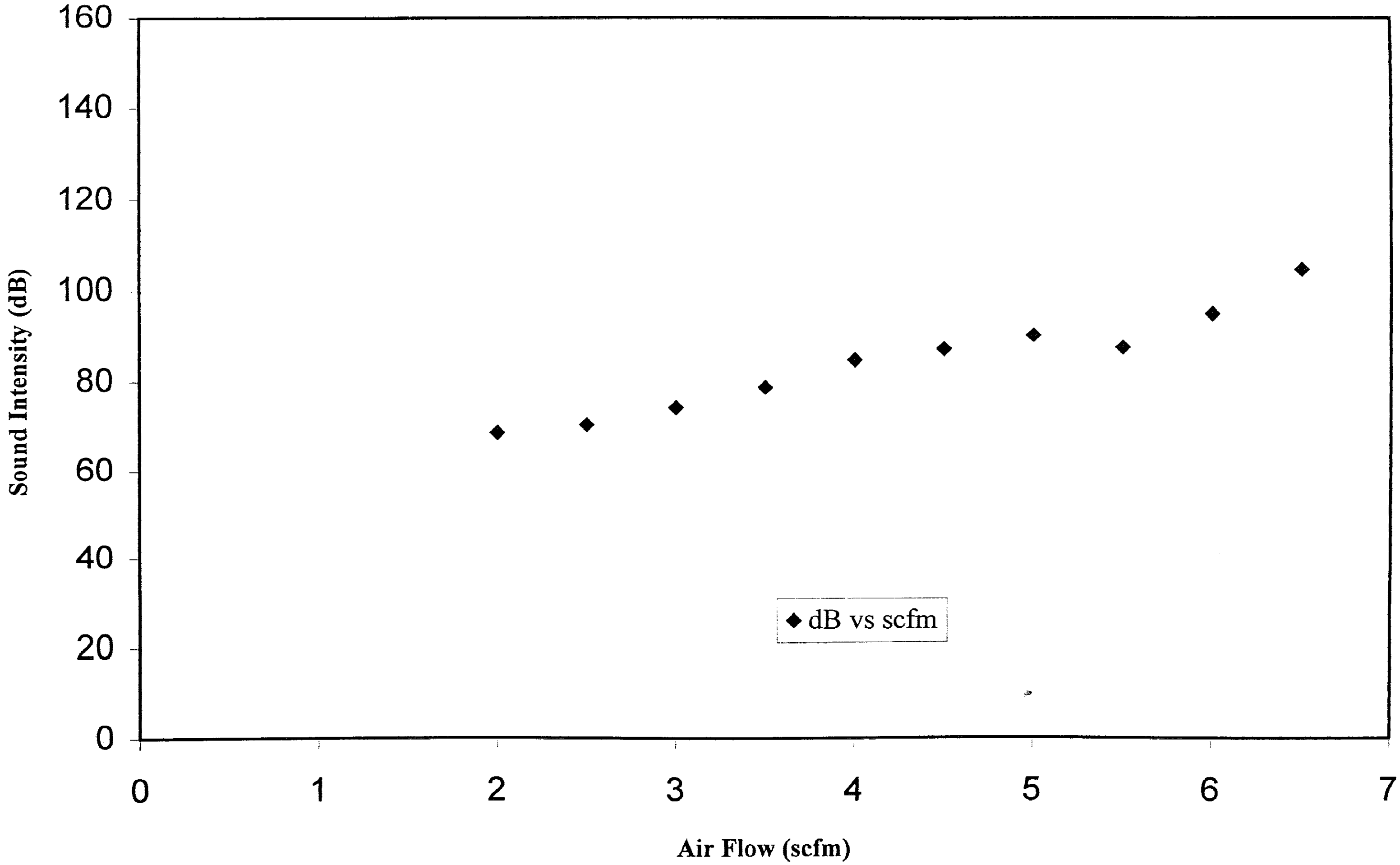


Figure A.1 Plot of Sound Intensity versus Air Flow at 100 cm for Whistle No. 1

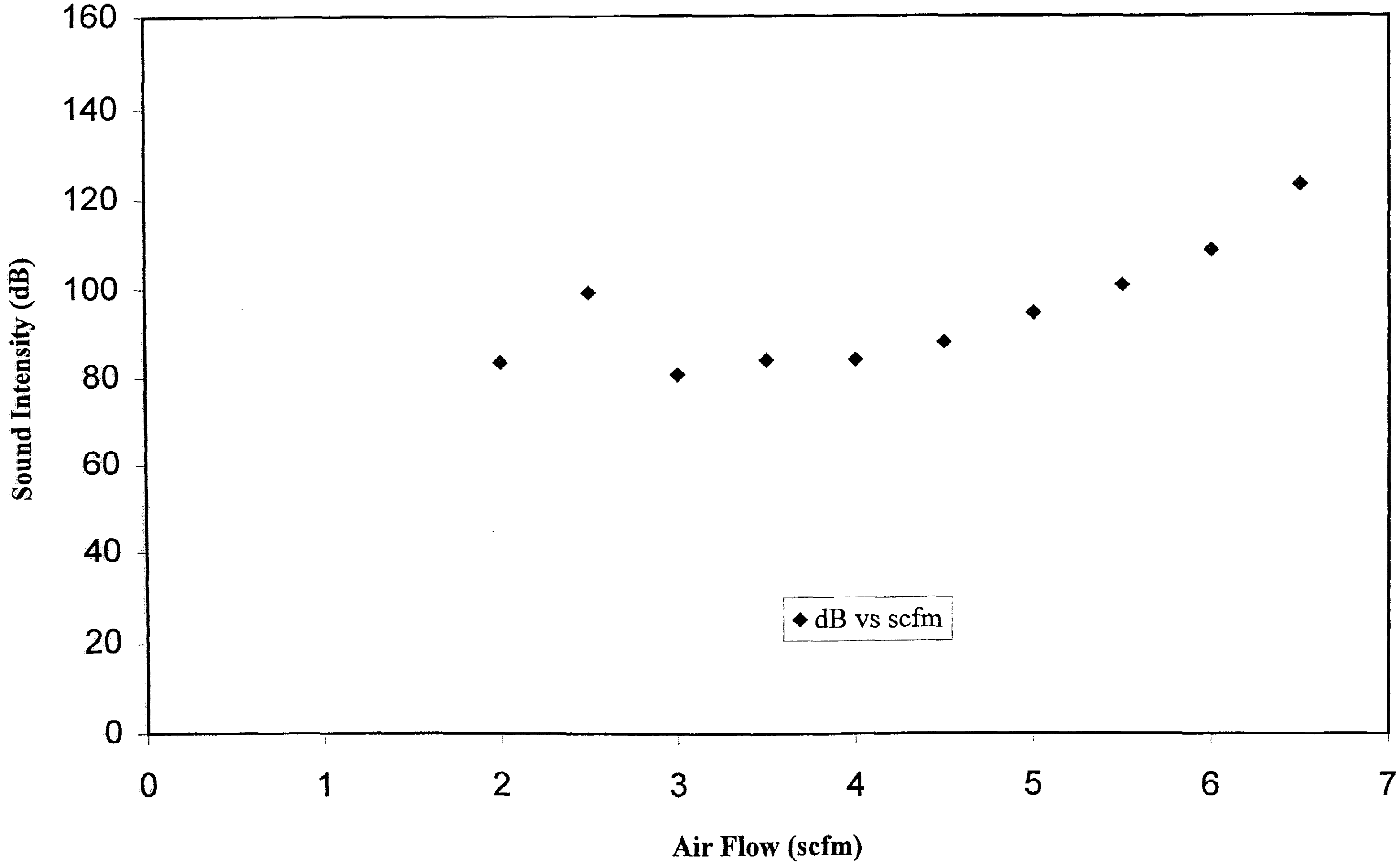


Figure A.2 Plot of Sound Intensity versus Air Flow at 100 cm for Whistle No. 2

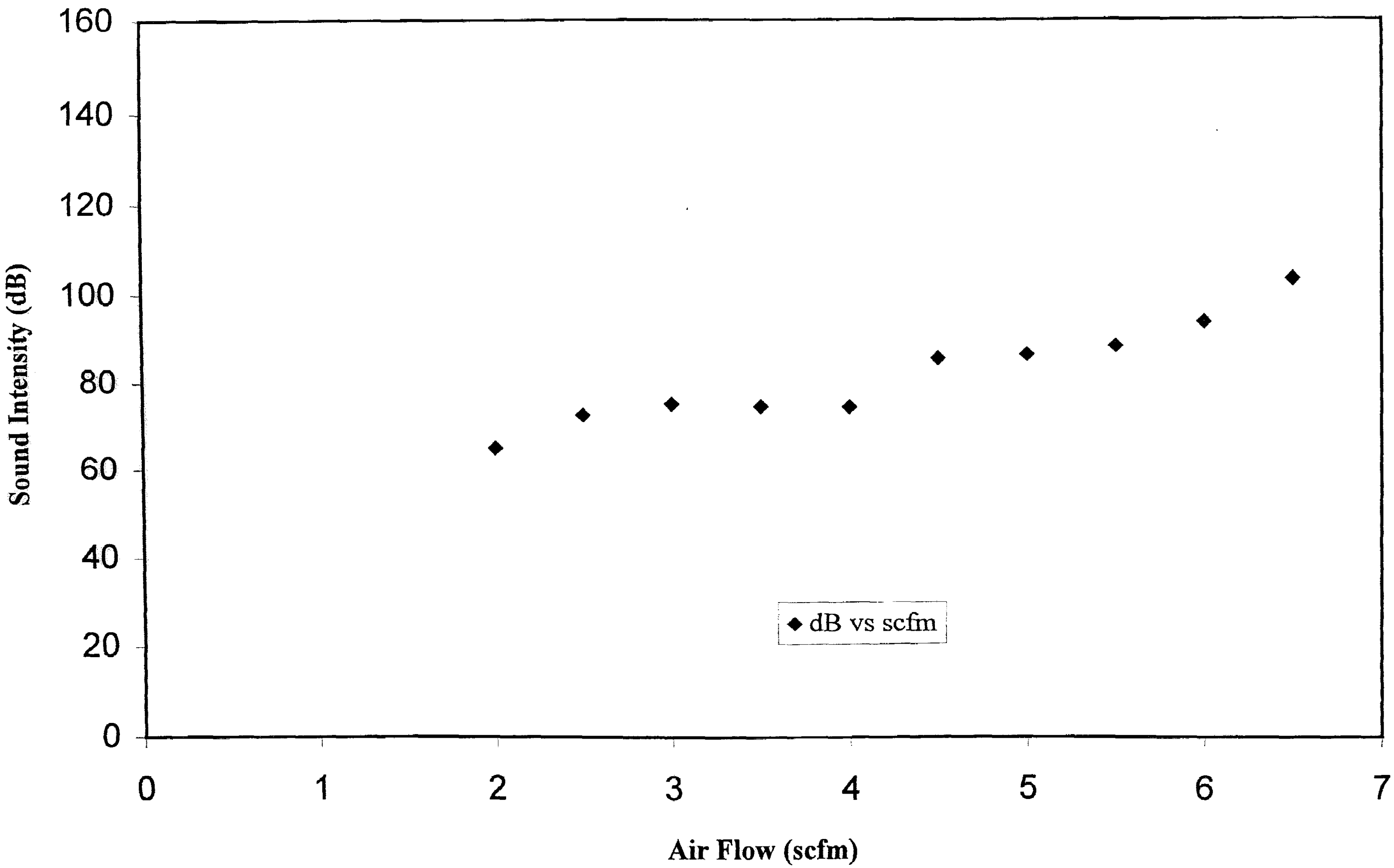


Figure A.3 Plot of Sound Intensity versus Air Flow at 100 cm for Whistle No. 3

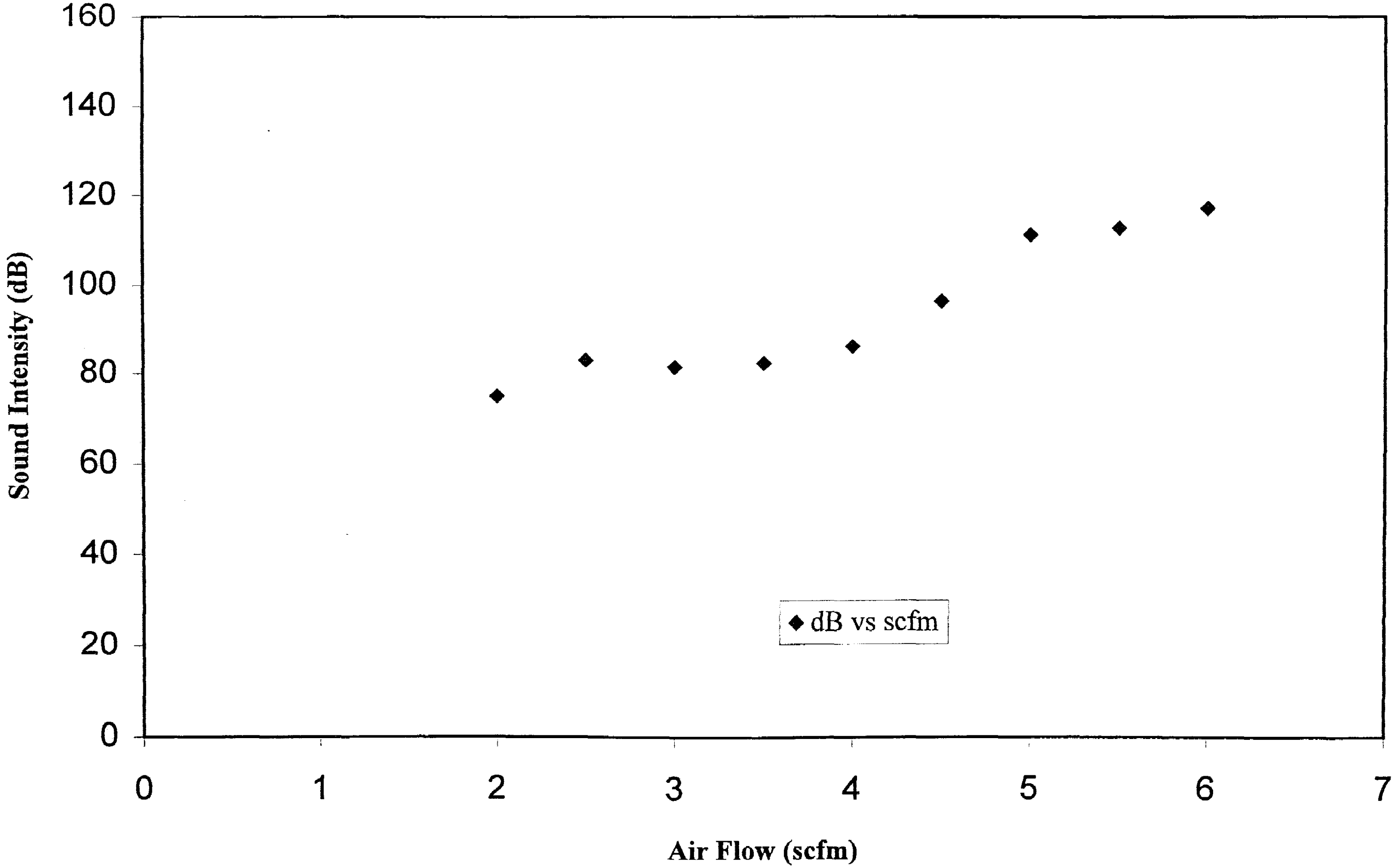


Figure A.4 Plot of Sound Intensity versus Air Flow at 100 cm for Whistle No. 4

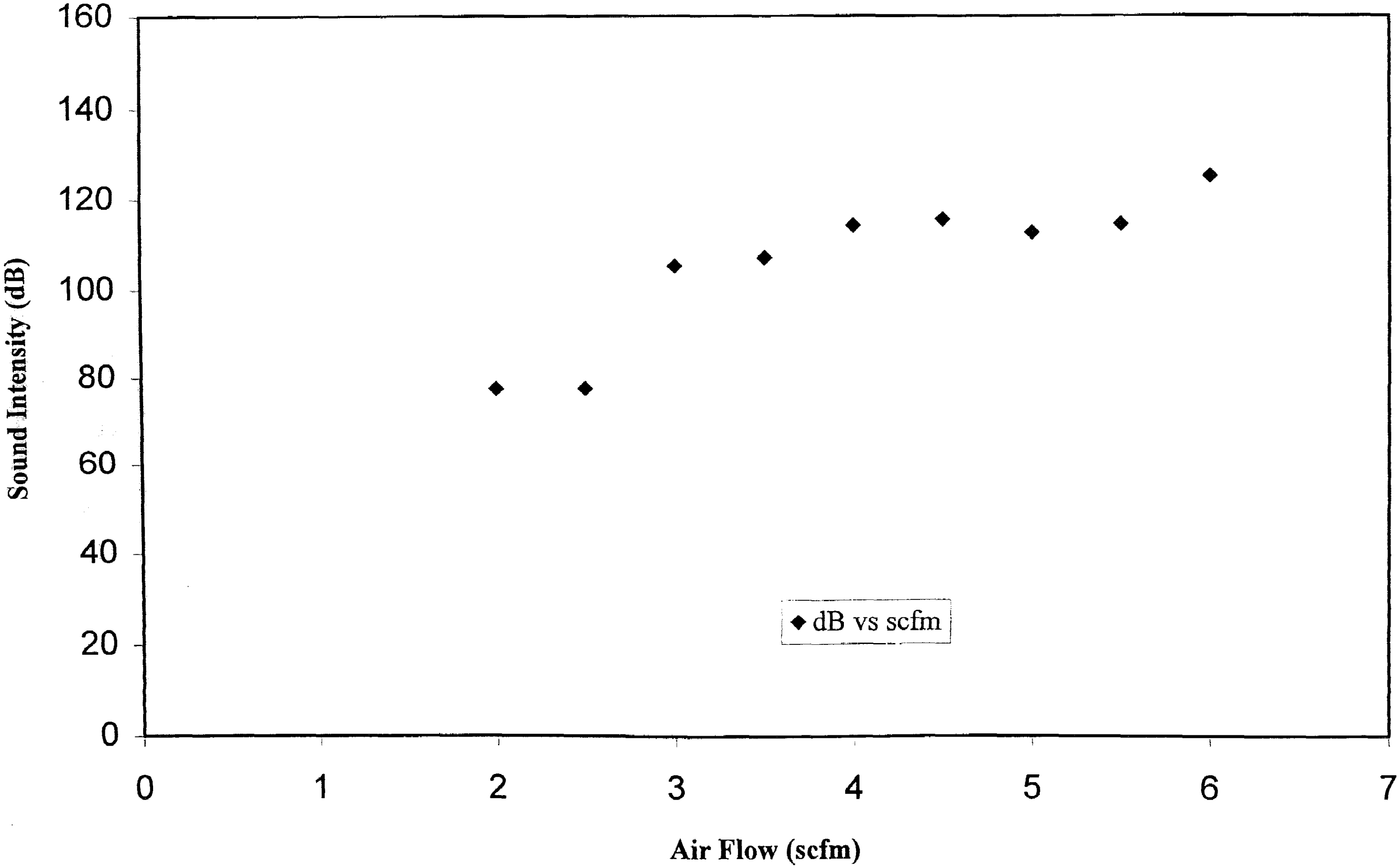


Figure A.5 Plot of Sound Intensity versus Air Flow at 100 cm for Whistle No. 5

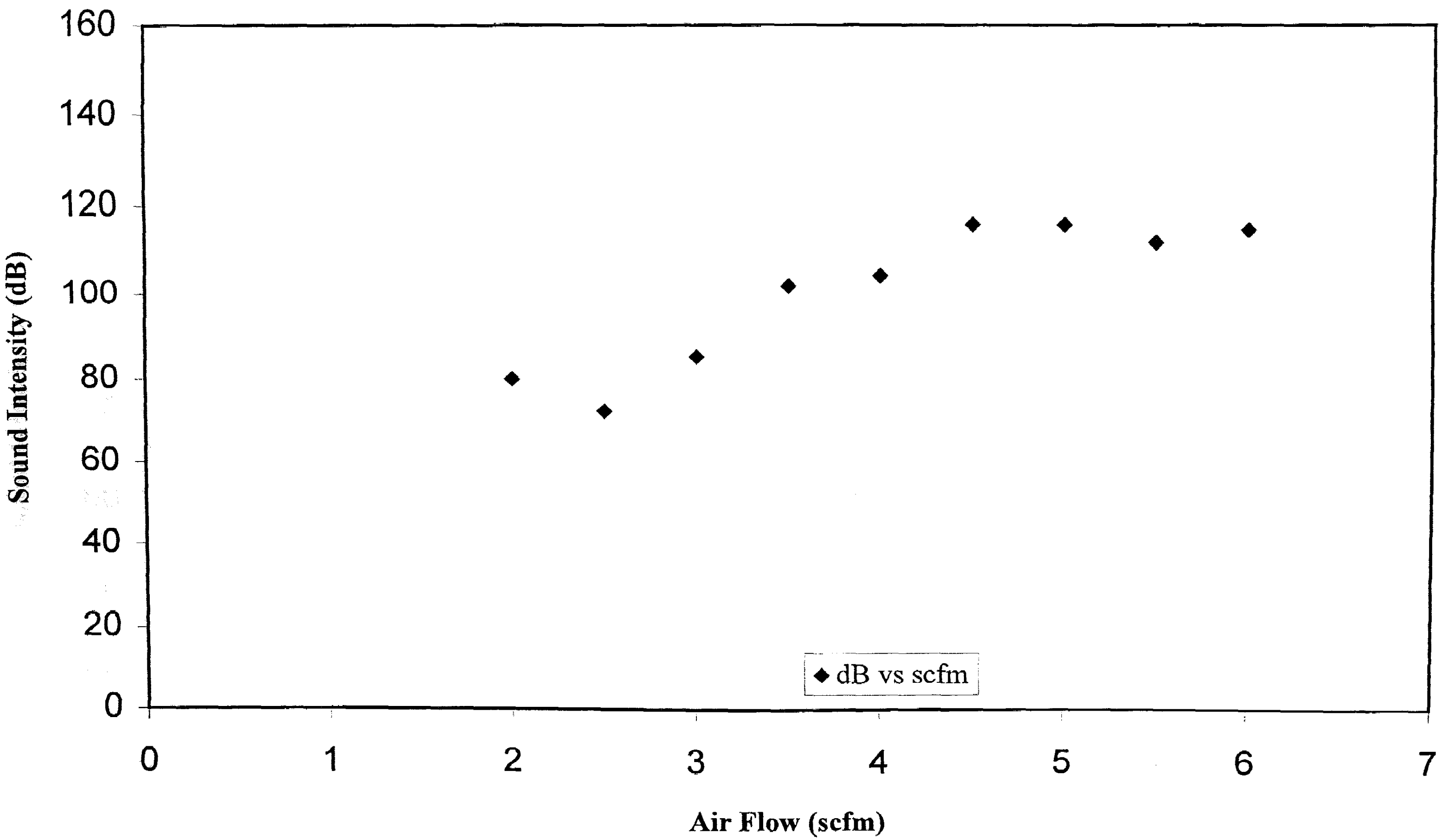


Figure A.6 Plot of Sound Intensity versus Air Flow at 100 cm for Whistle Nos. 4 and 5

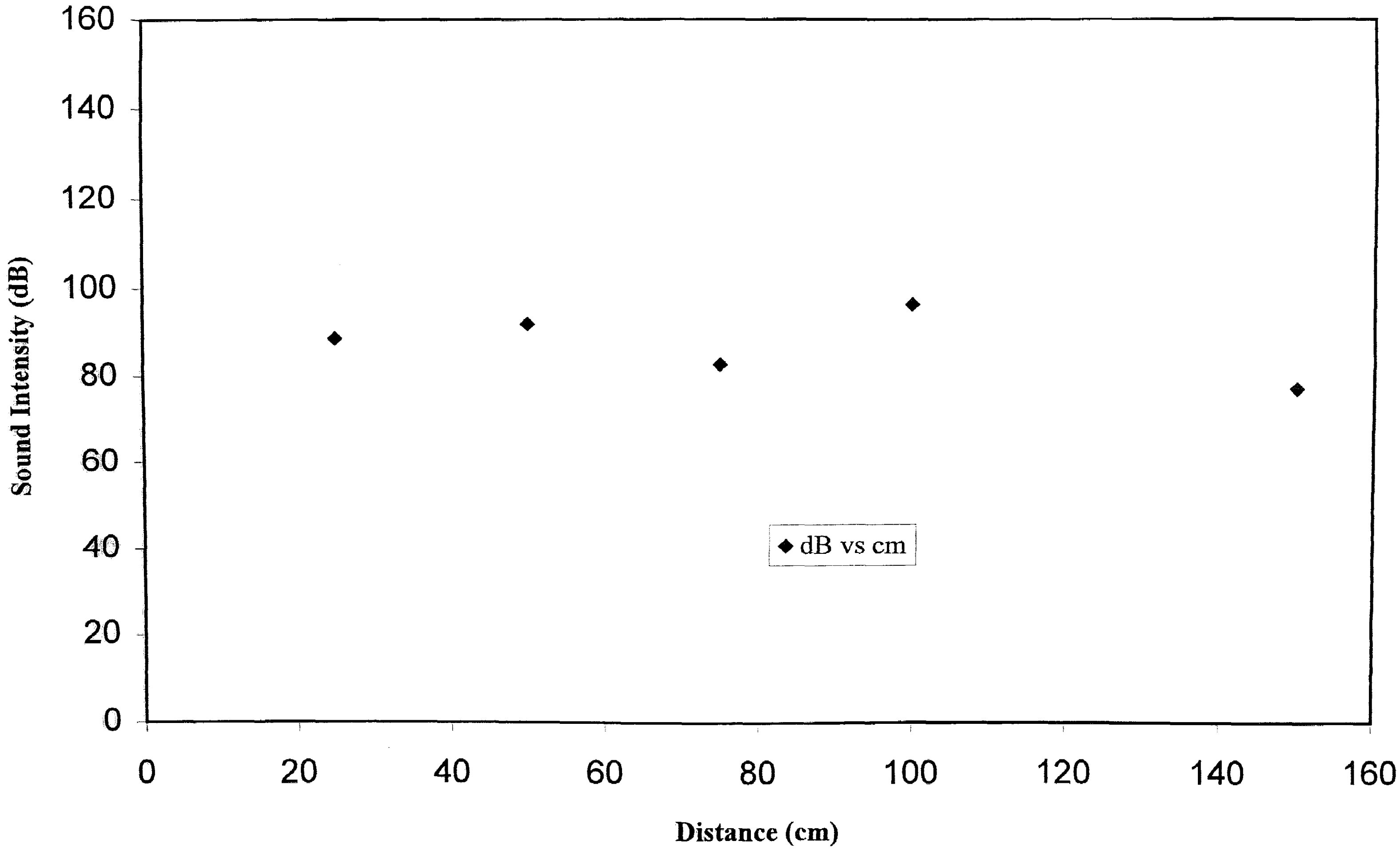


Figure A.7 Plot of Sound Intensity versus Distance at 4.5 scfm for Whistle No. 4

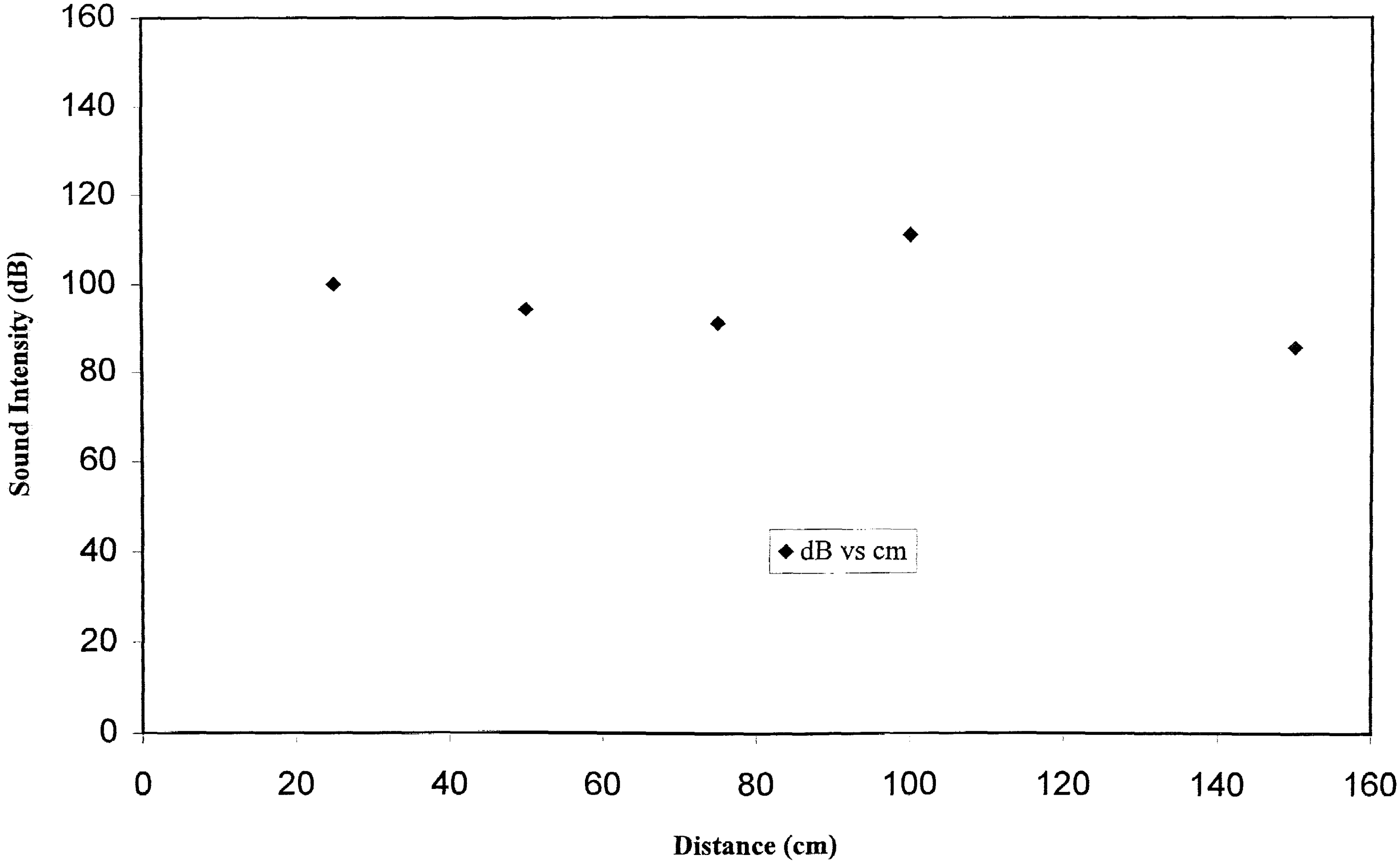


Figure A.8 Plot of Sound Intensity versus Distance at 5 scfm for Whistle No. 4

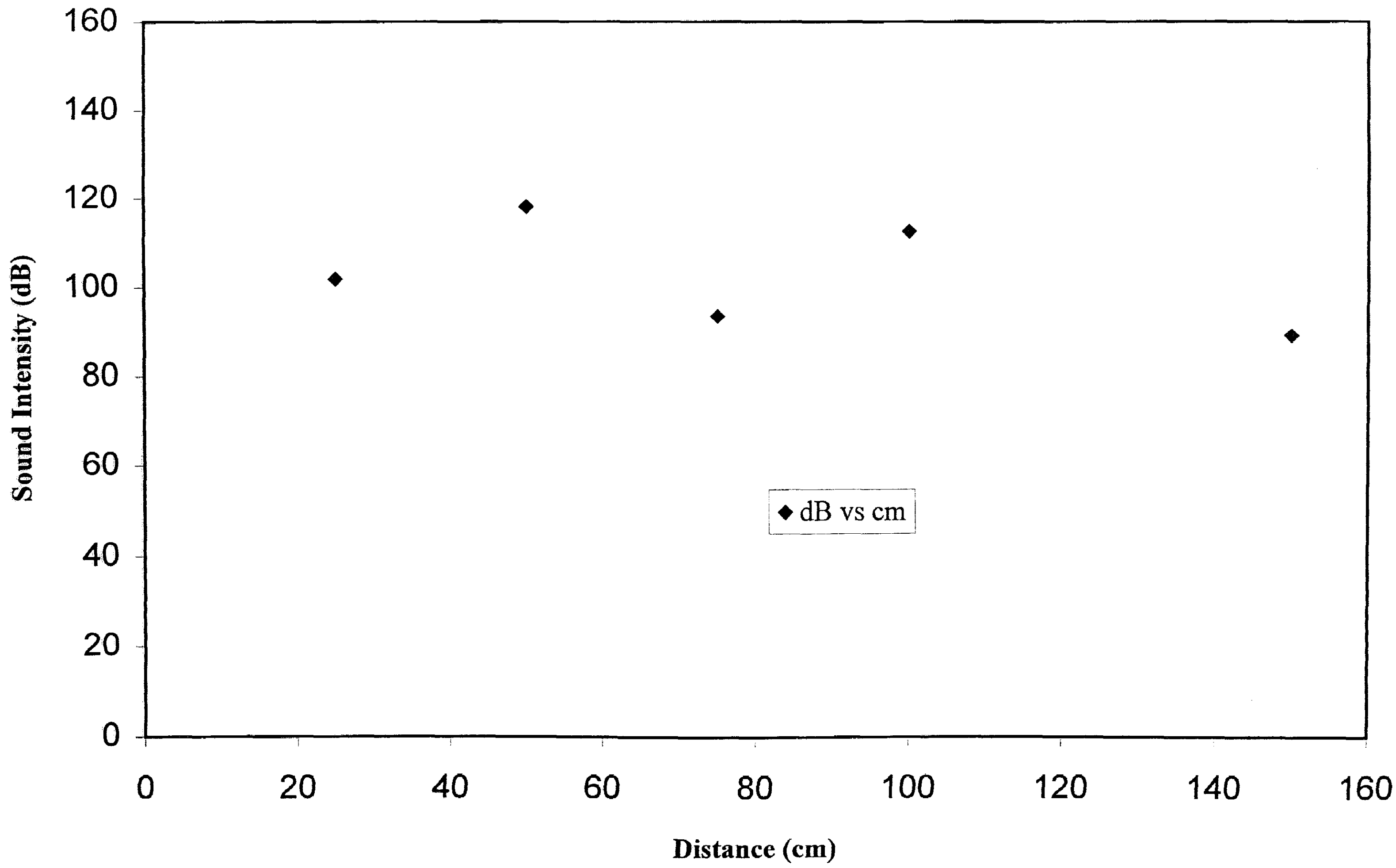


Figure A.9 Plot of Sound Intensity versus Distance at 5.5 scfm for Whistle No. 4

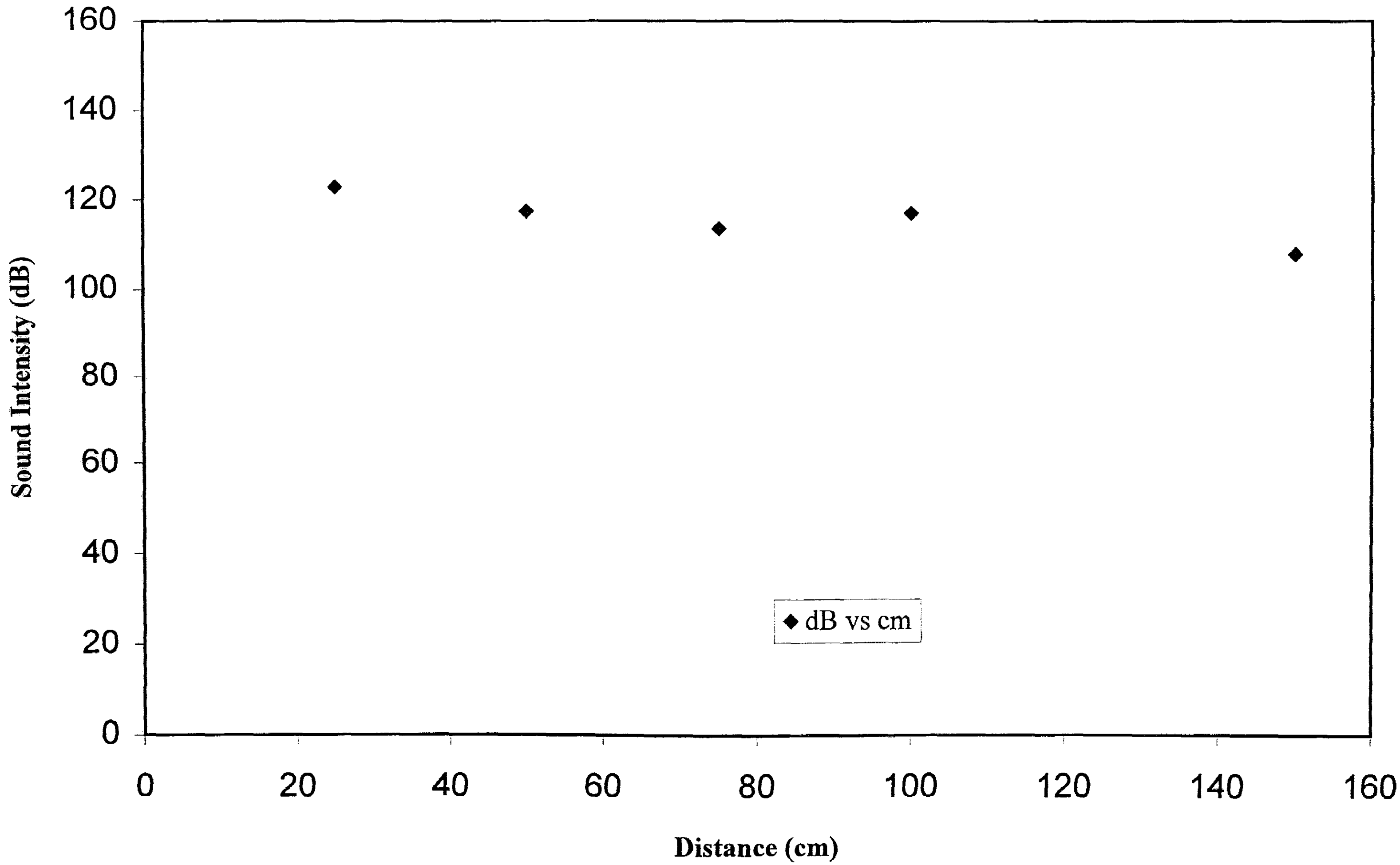


Figure A.10 Plot of Sound Intensity versus Distance at 6 scfm for Whistle No. 4

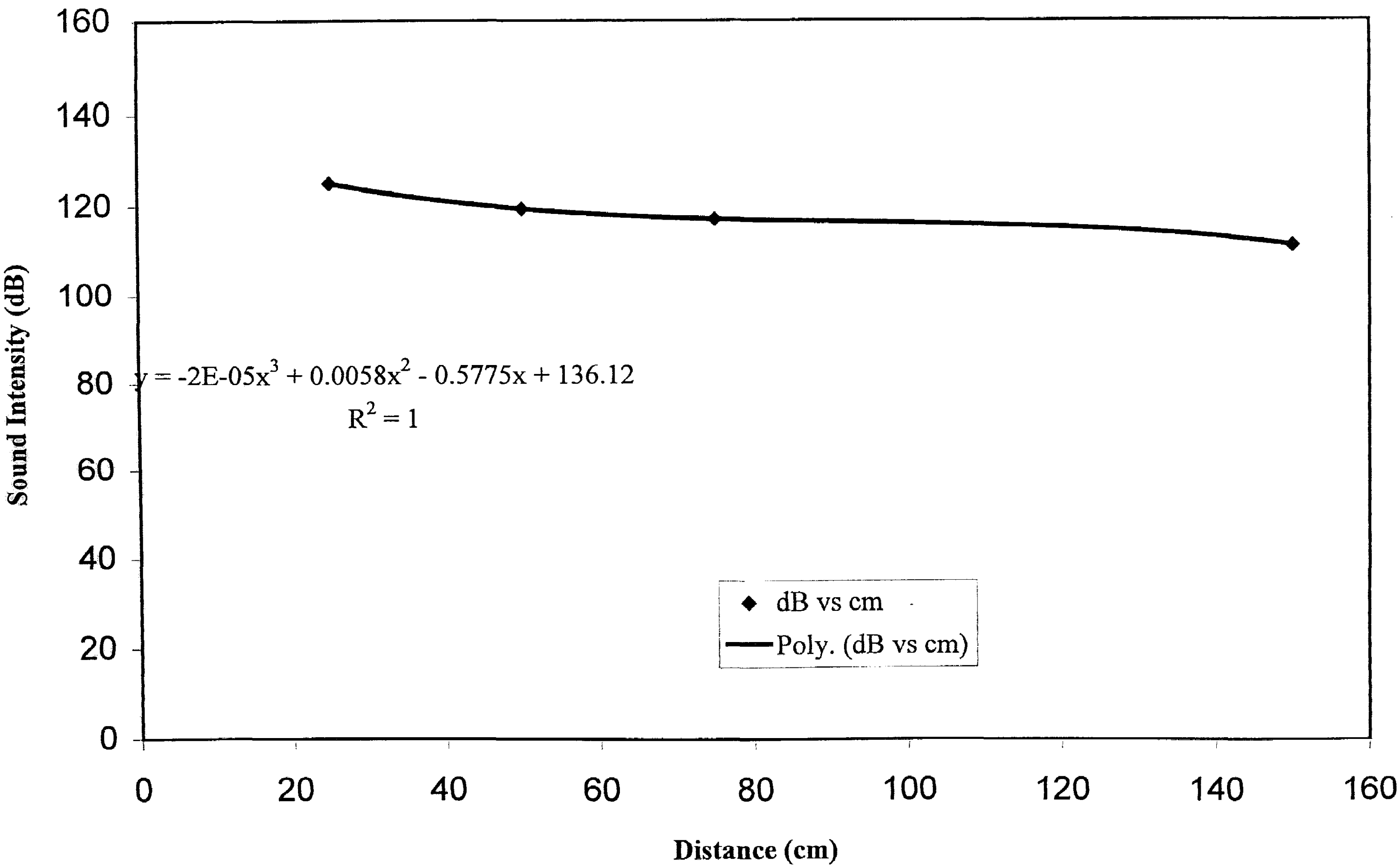


Figure A.11 Plot of Sound Intensity versus Distance at 6.5 scfm for Whistle No. 4

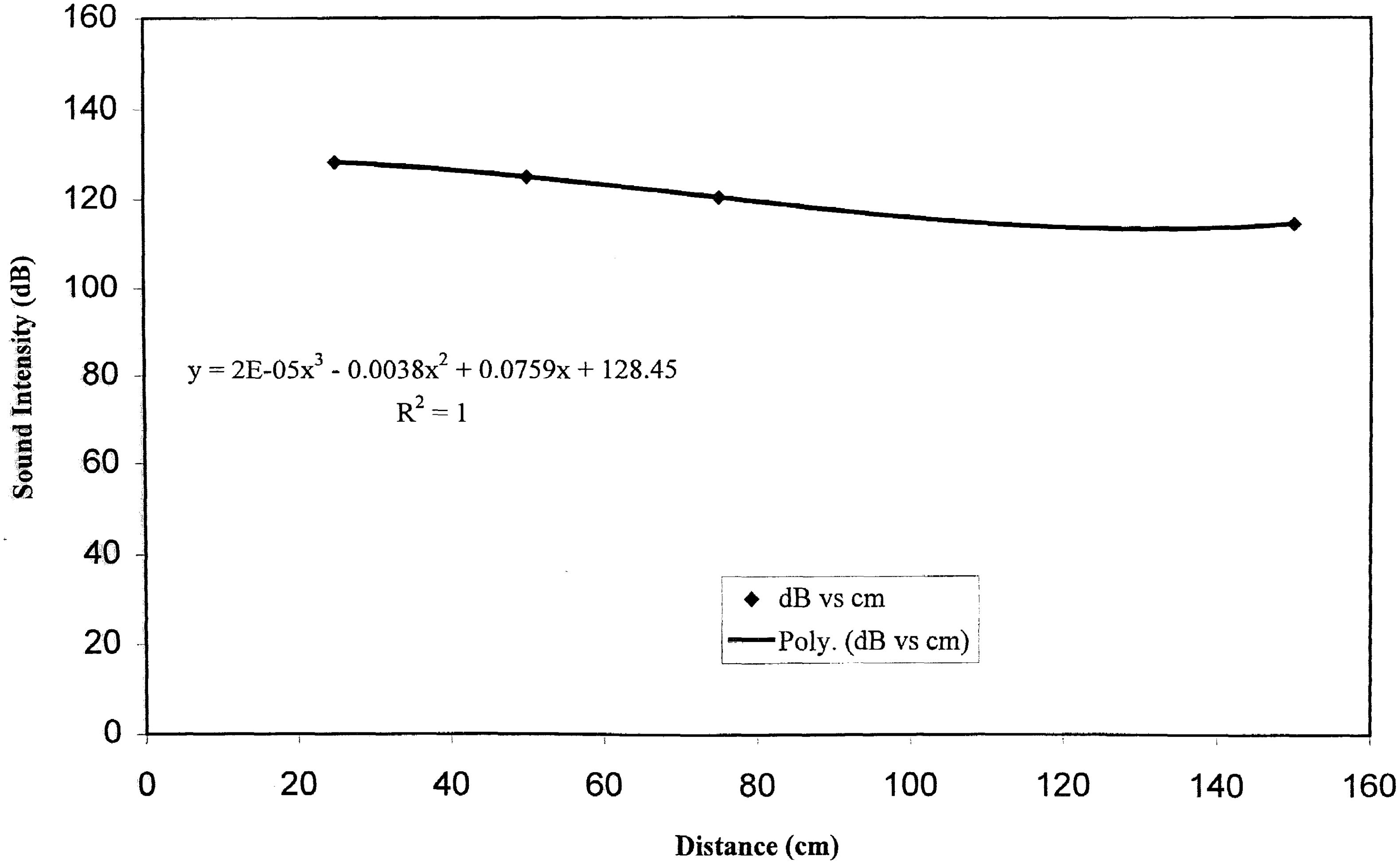


Figure A.12 Plot of Sound Intensity versus Distance at 7 scfm for Whistle No. 4

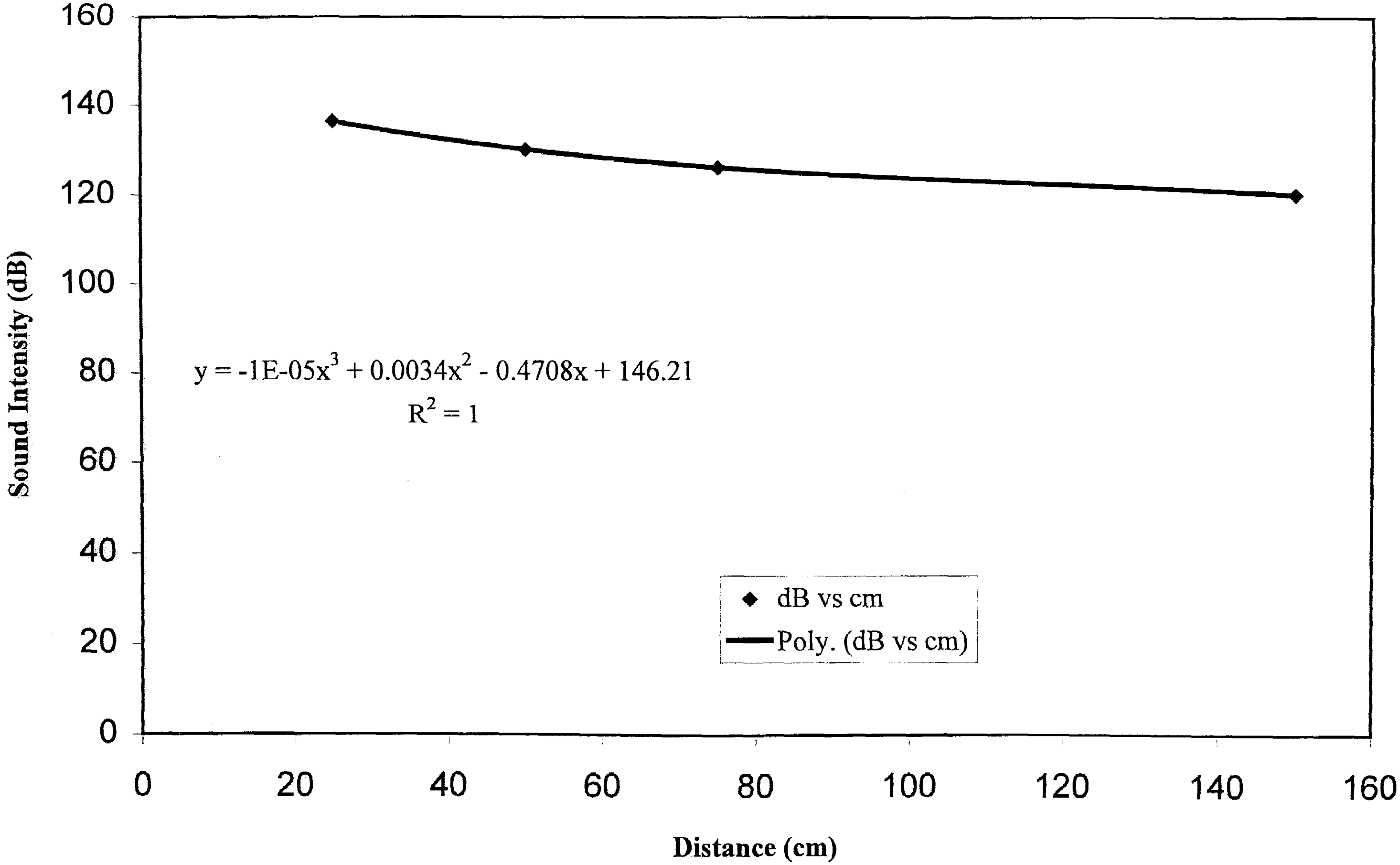


Figure A.13 Plot of Sound Intensity versus Distance at 7.5 scfm for Whistle No. 4

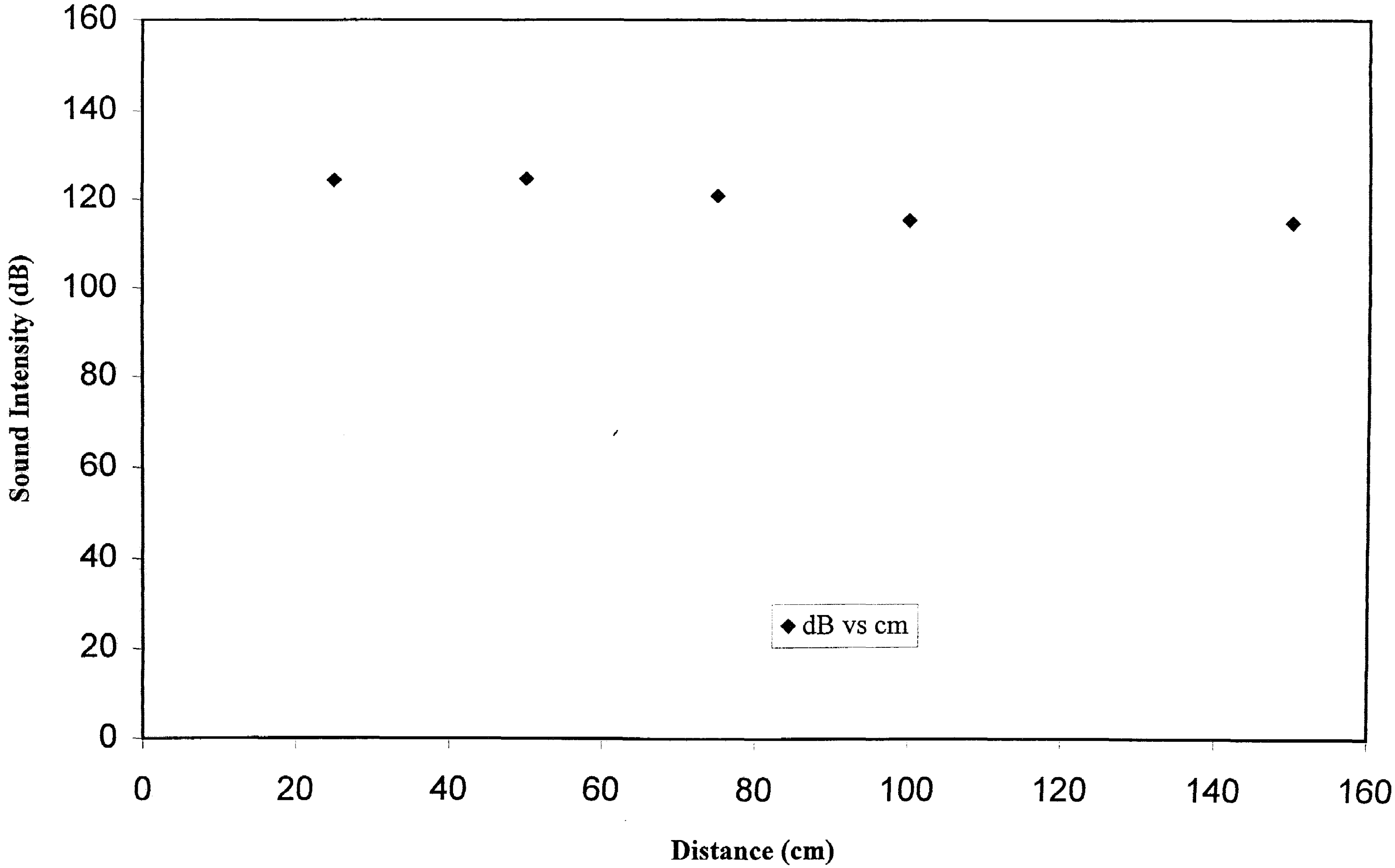


Figure A.14 Plot of Sound Intensity versus Distance at 4.5 scfm for Whistle No. 5

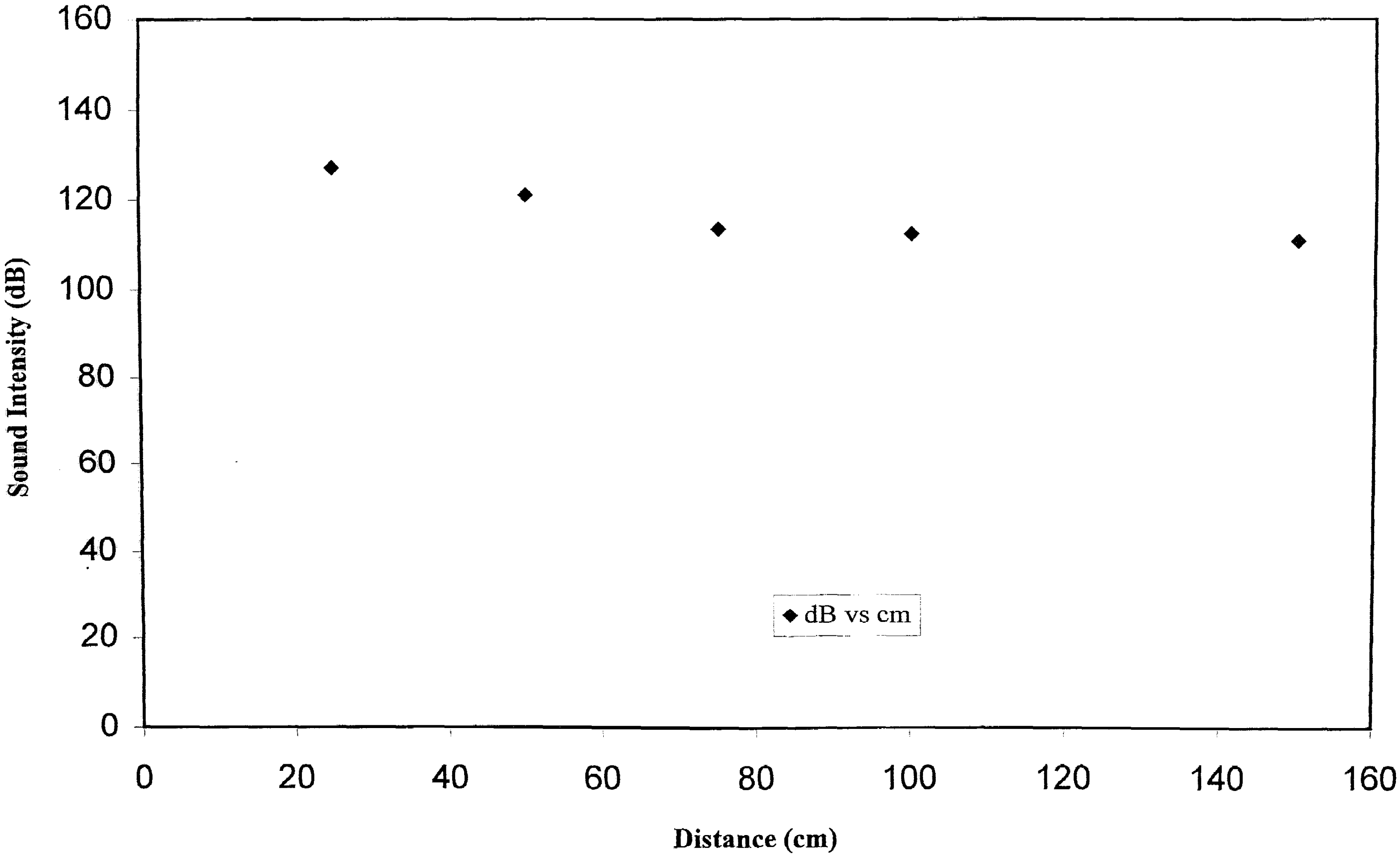


Figure A.15 Plot of Sound Intensity versus Distance at 5 scfm for Whistle No. 5

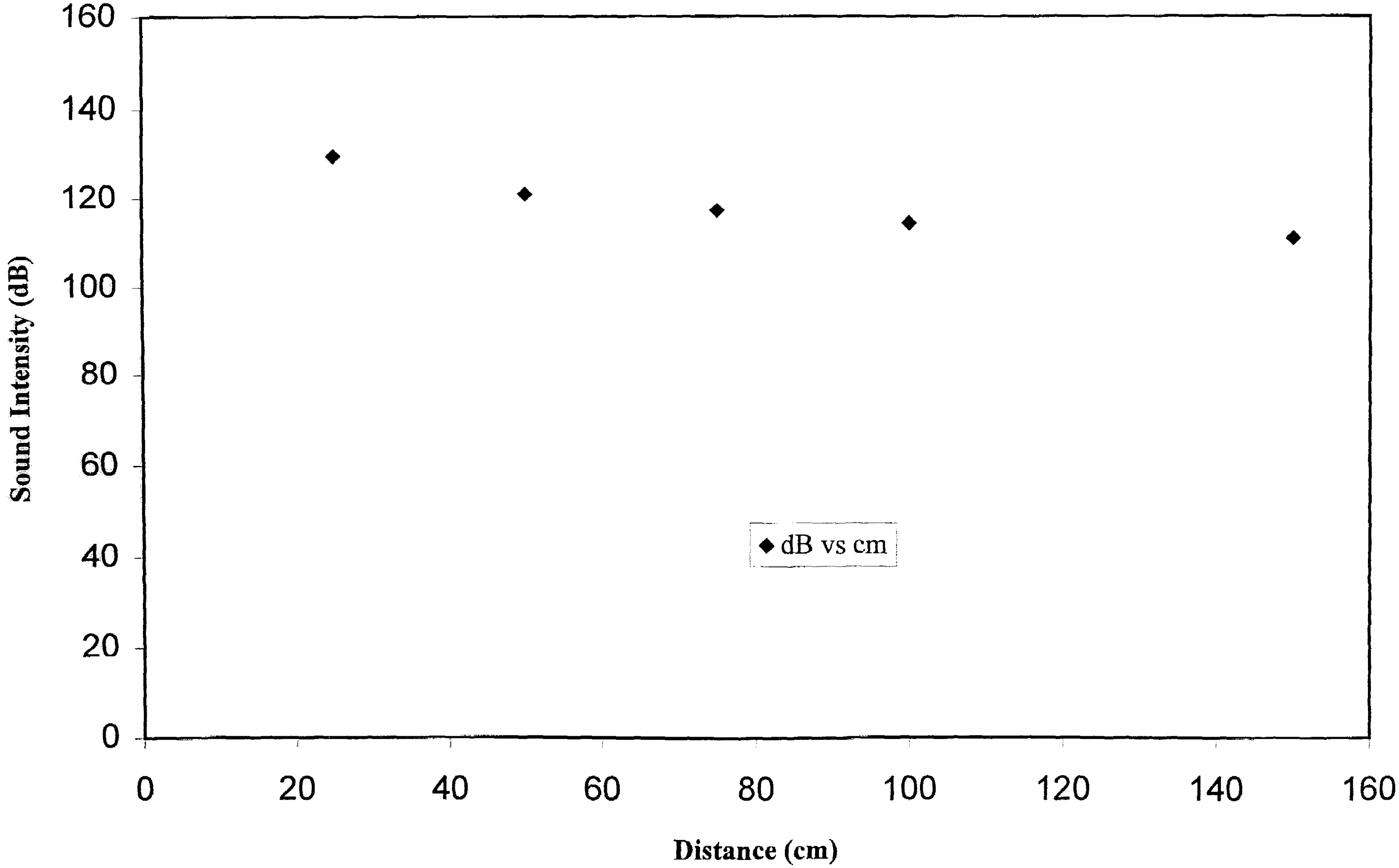


Figure A.16 Plot of Sound Intensity versus Distance at 5.5 scfm for Whistle No. 5

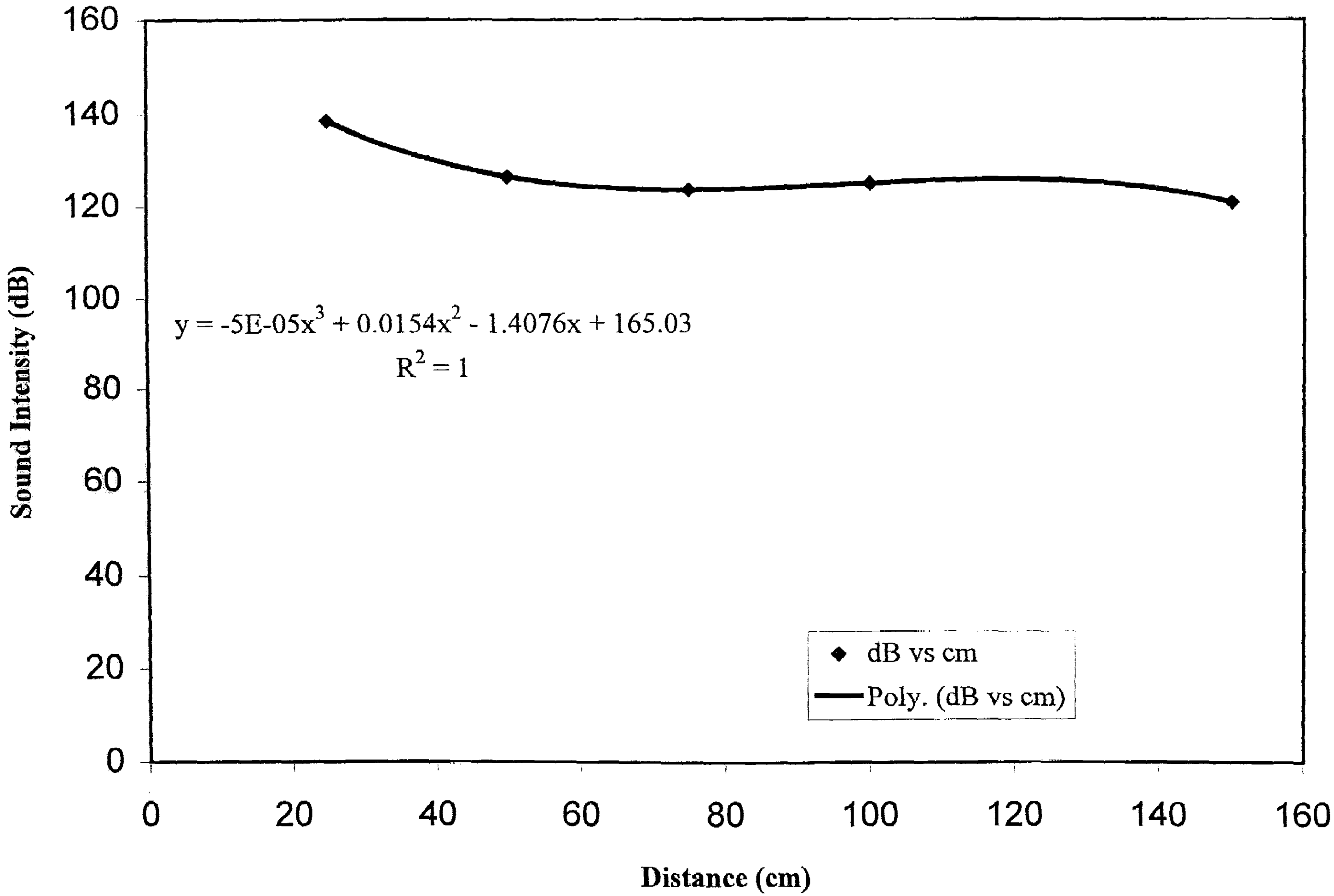


Figure A.17 Plot of Sound Intensity versus Distance at 6 scfm for Whistle No. 5

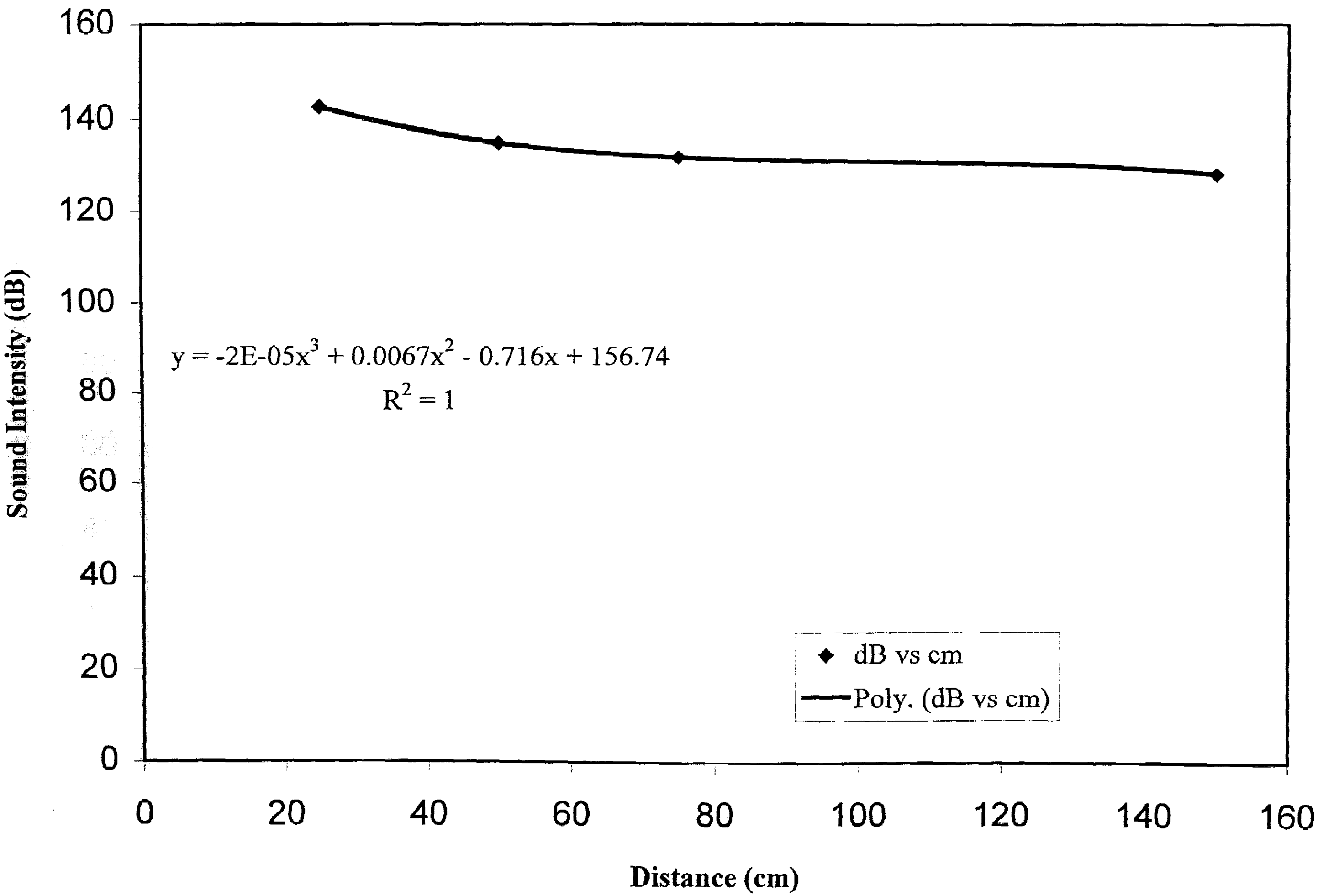


Figure A.18 Plot of Sound Intensity versus Distance at 6.5 scfm for Whistle No. 5

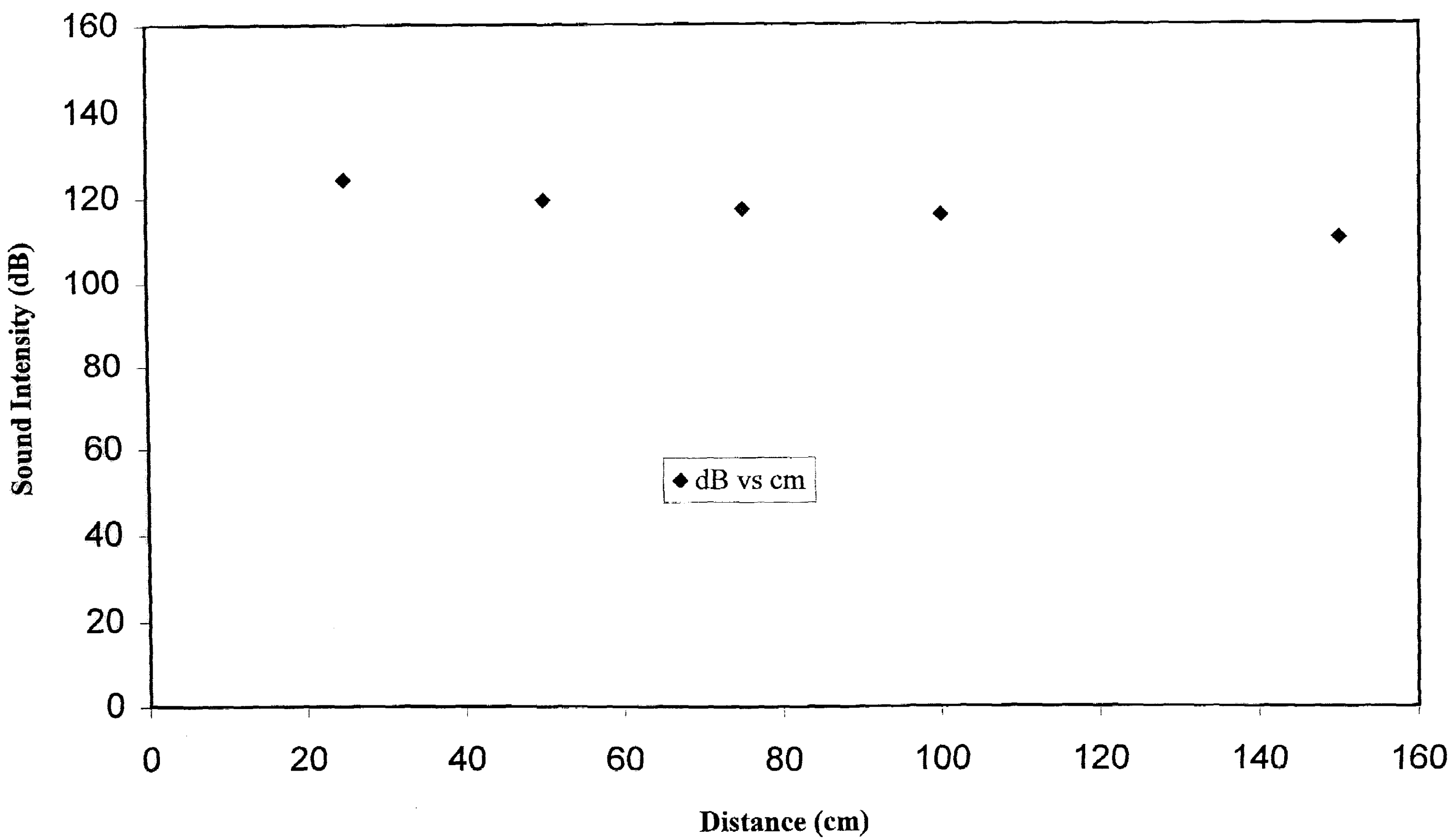


Figure A.19 Plot of Sound Intensity versus Distance at 5 scfm for combined Whistle Nos. 4 and 5

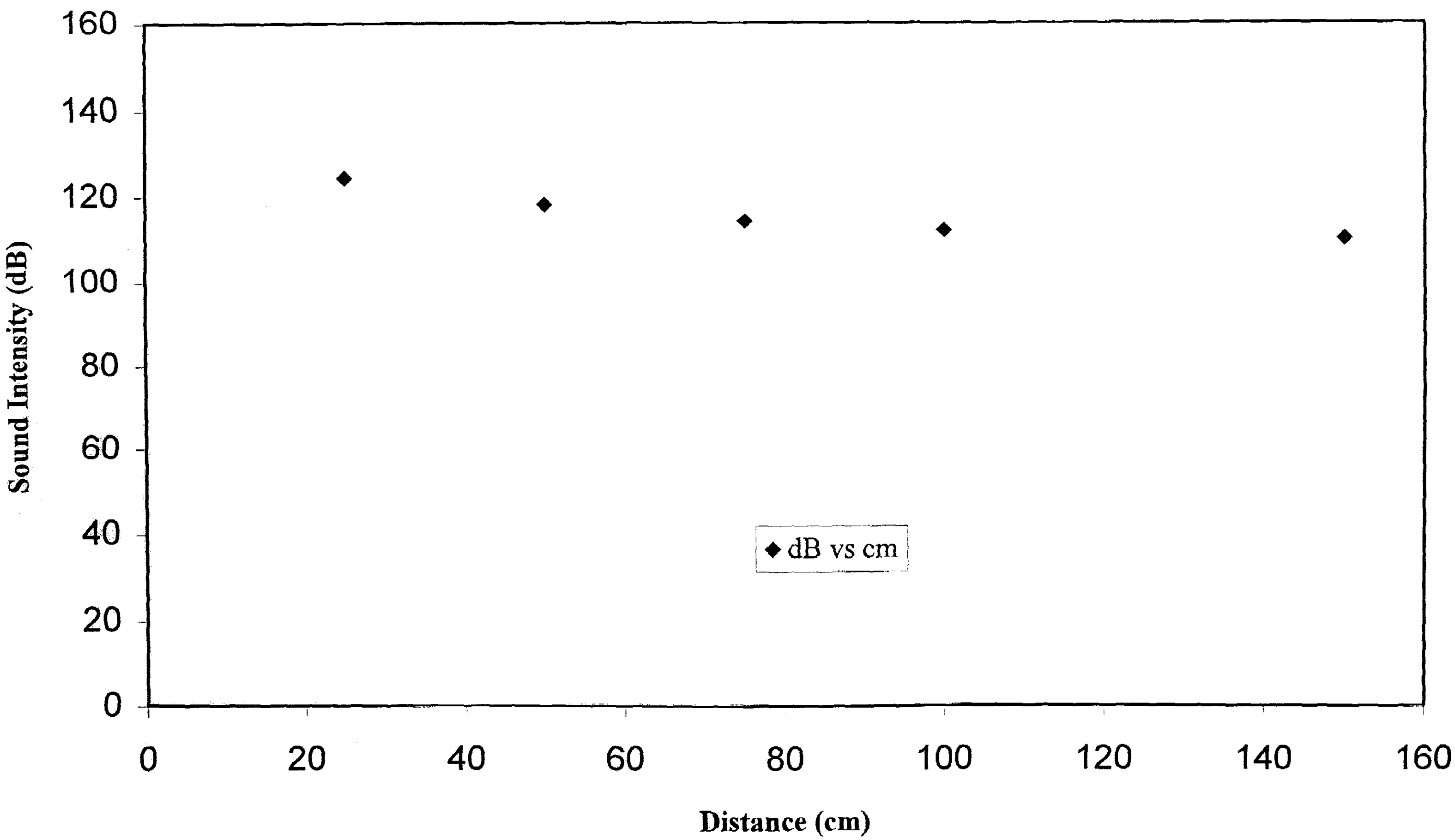


Figure A.20 Plot of Sound Intensity versus Distance at 5.5 scfm for combined Whistle No.4 and 5

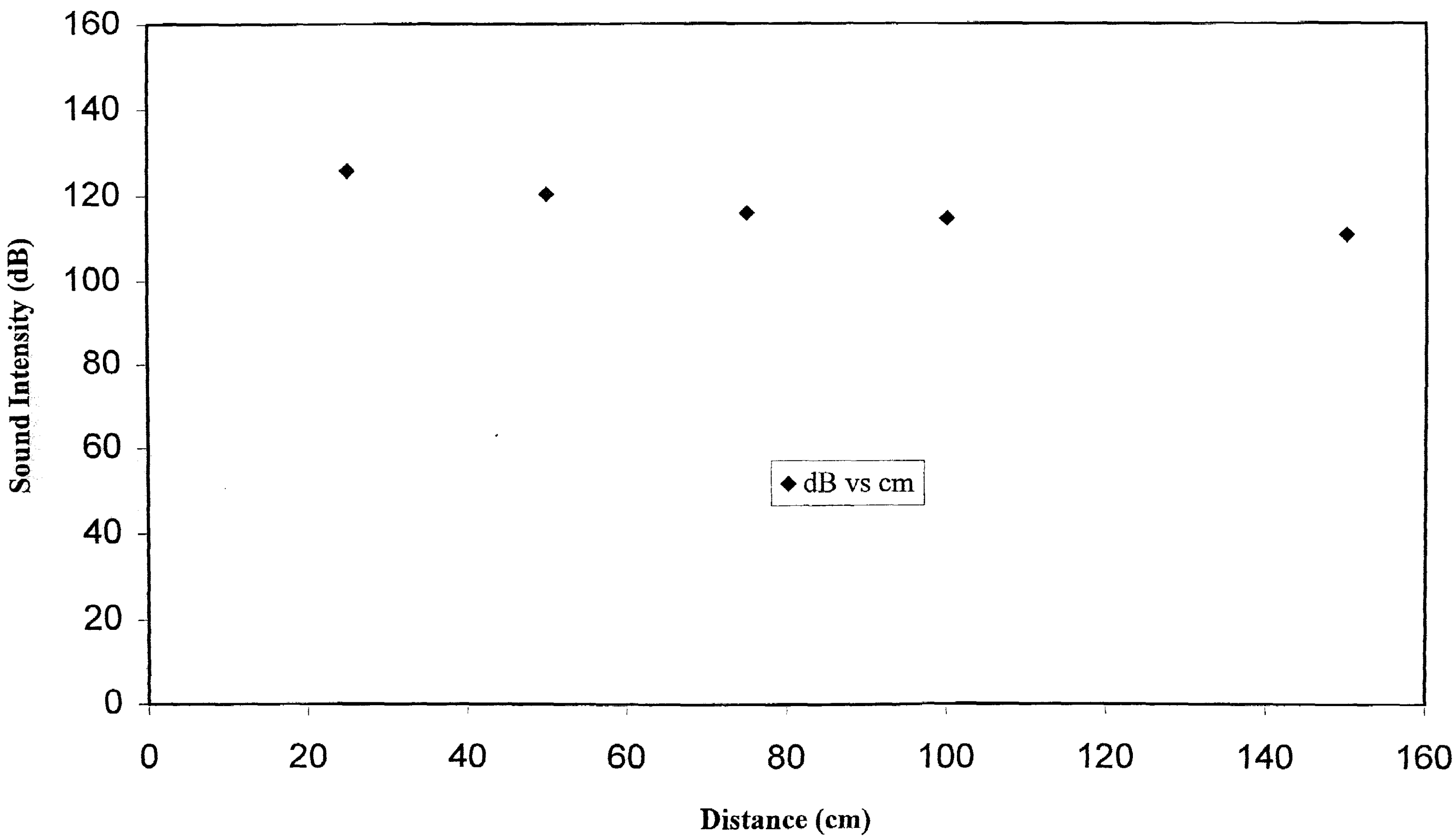


Figure A.21 Plot of Sound Intensity versus Distance for Whistle No. 4 at 6 scfm and Whistle No. 5 at 5.5 scfm

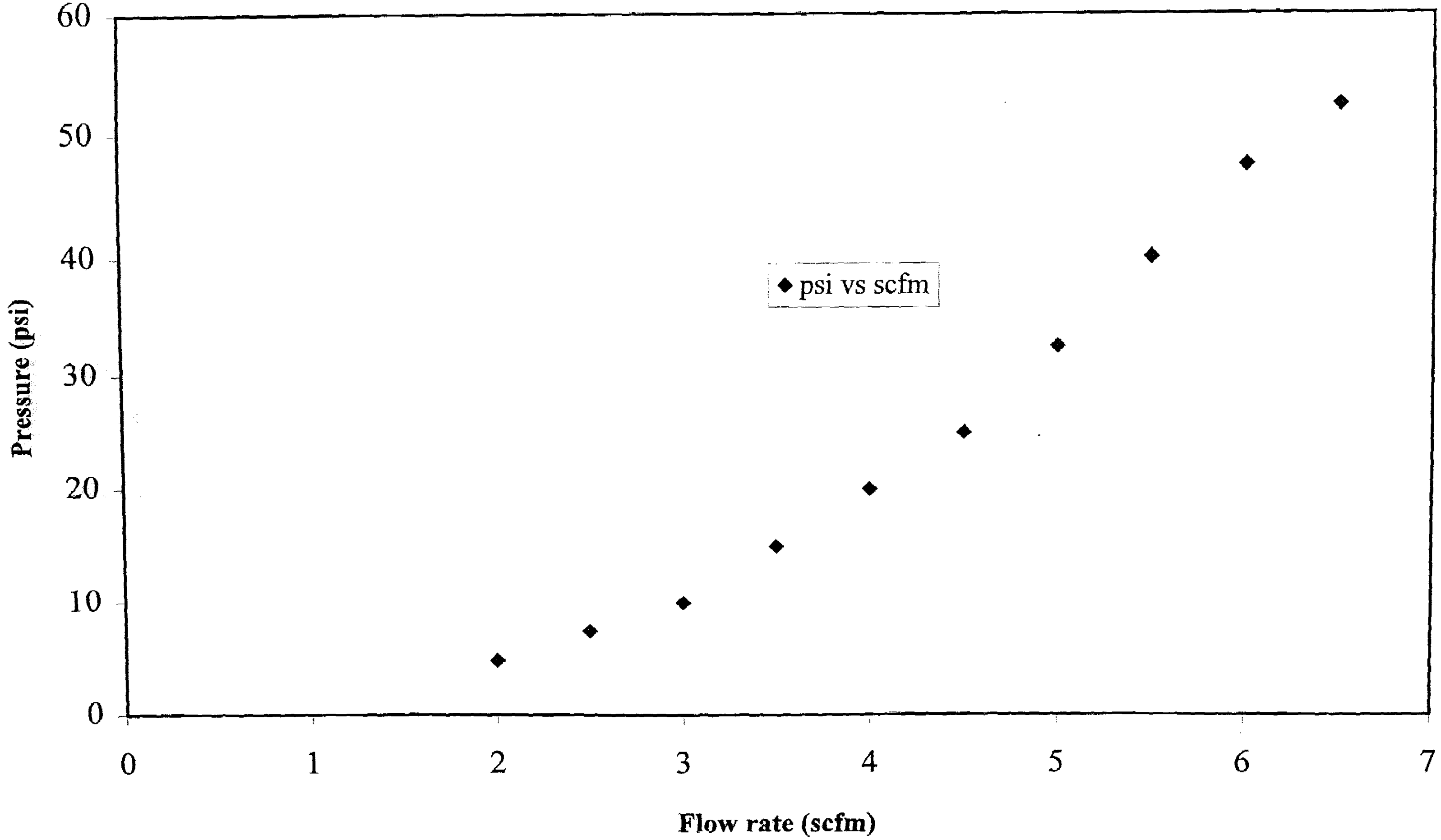


Figure A.22 Plot of Pressure versus Flowrate for Whistle No. 1 at 100 cm

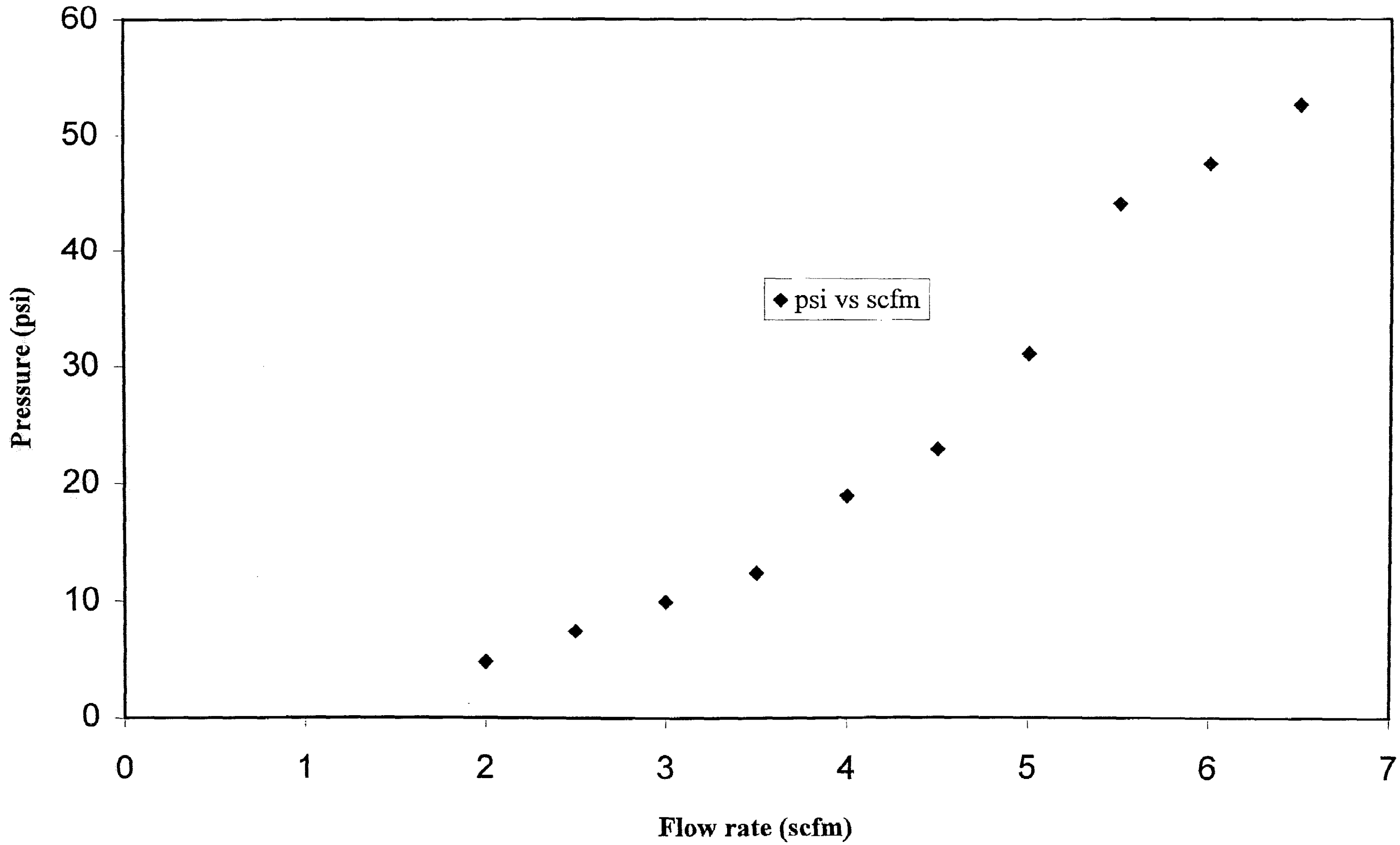


Figure A.23 Plot of Pressure versus Flowrate for Whistle No. 2 at 100 cm

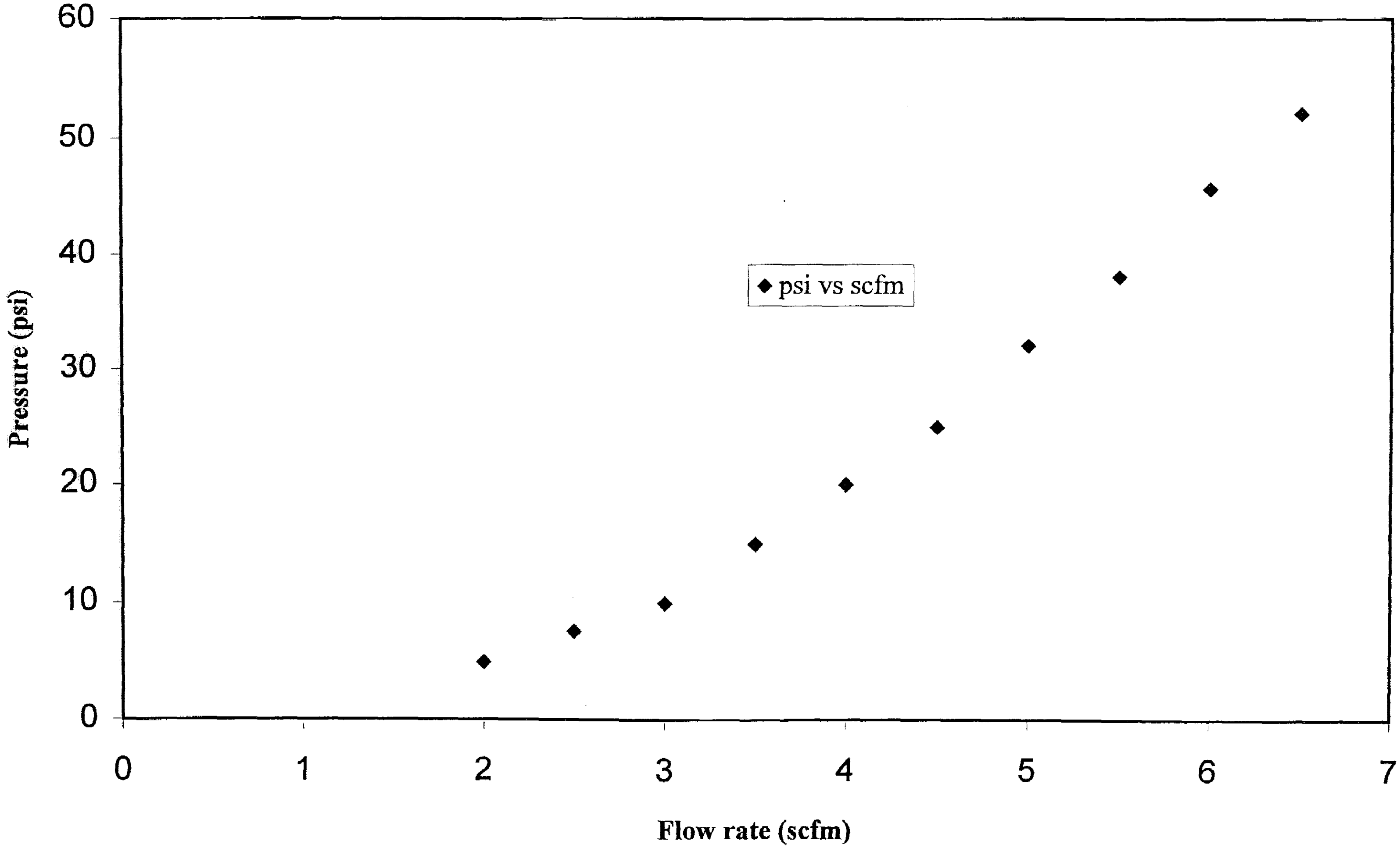


Figure A.24 Plot of Pressure versus Flowrate for Whistle No. 3 at 100 cm

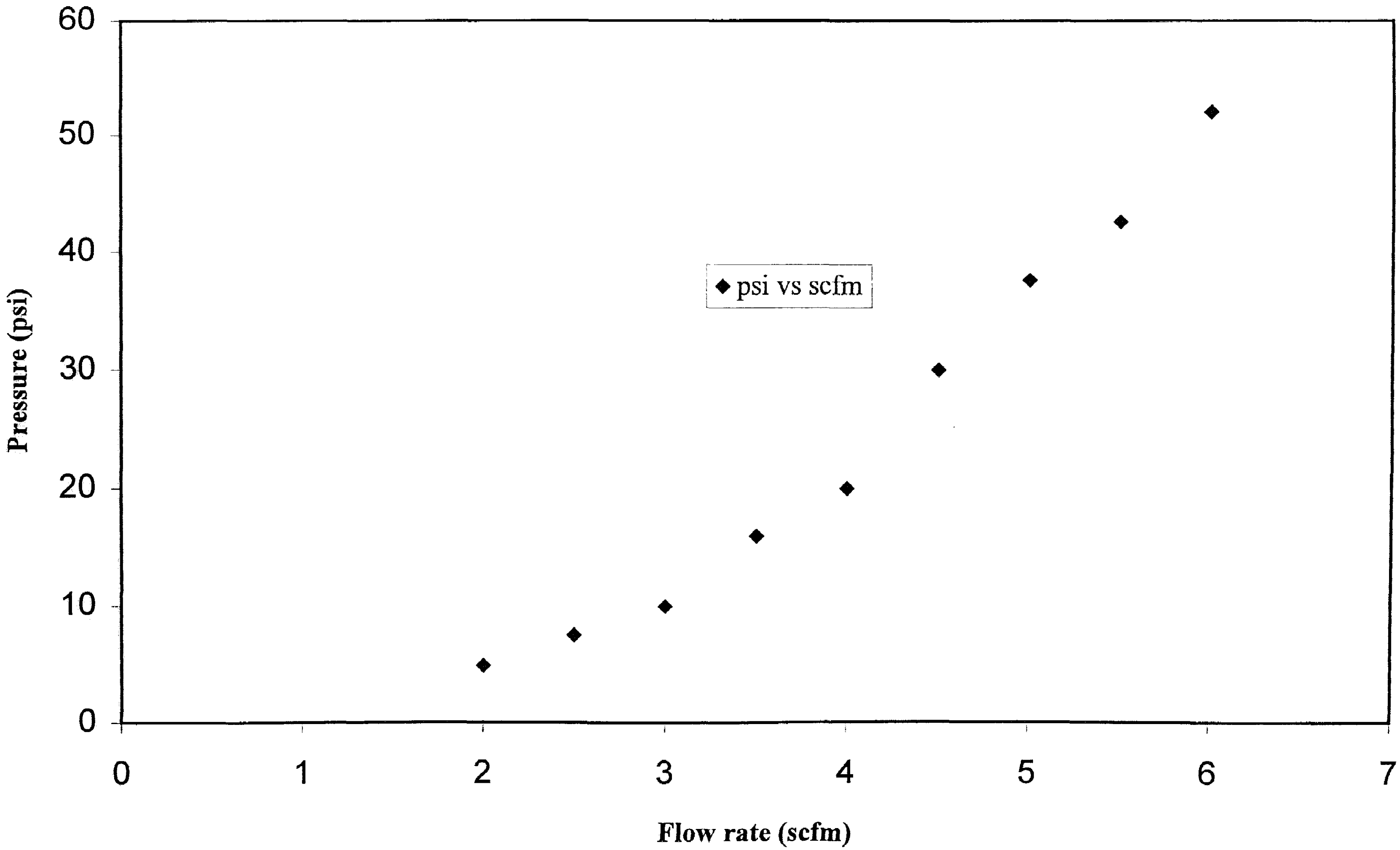


Figure A.25 Plot of Pressure versus Flowrate for Whistle No. 4 at 100 cm

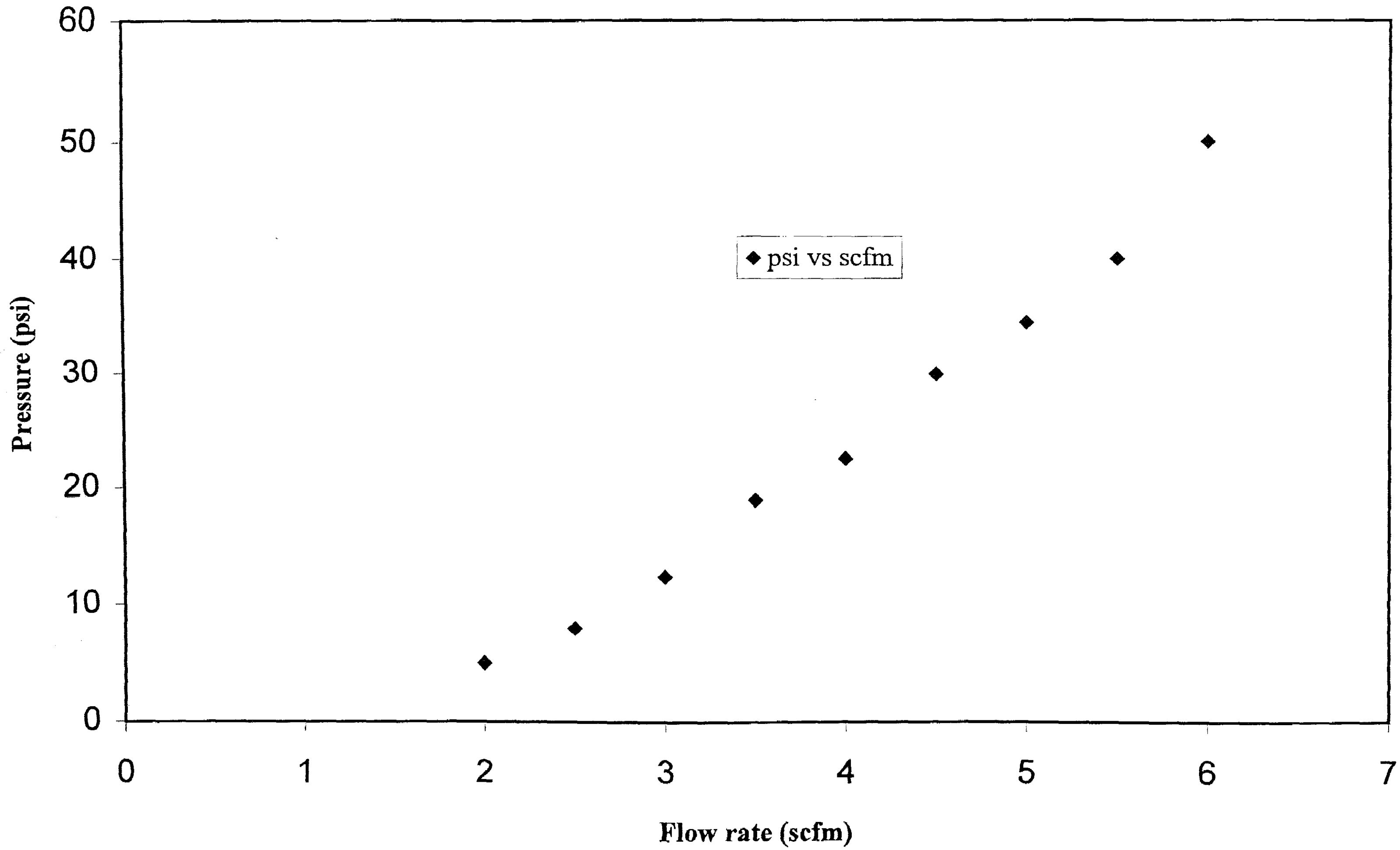


Figure A.26 Plot of Pressure versus Flowrate for Whistle No. 5 at 100 cm

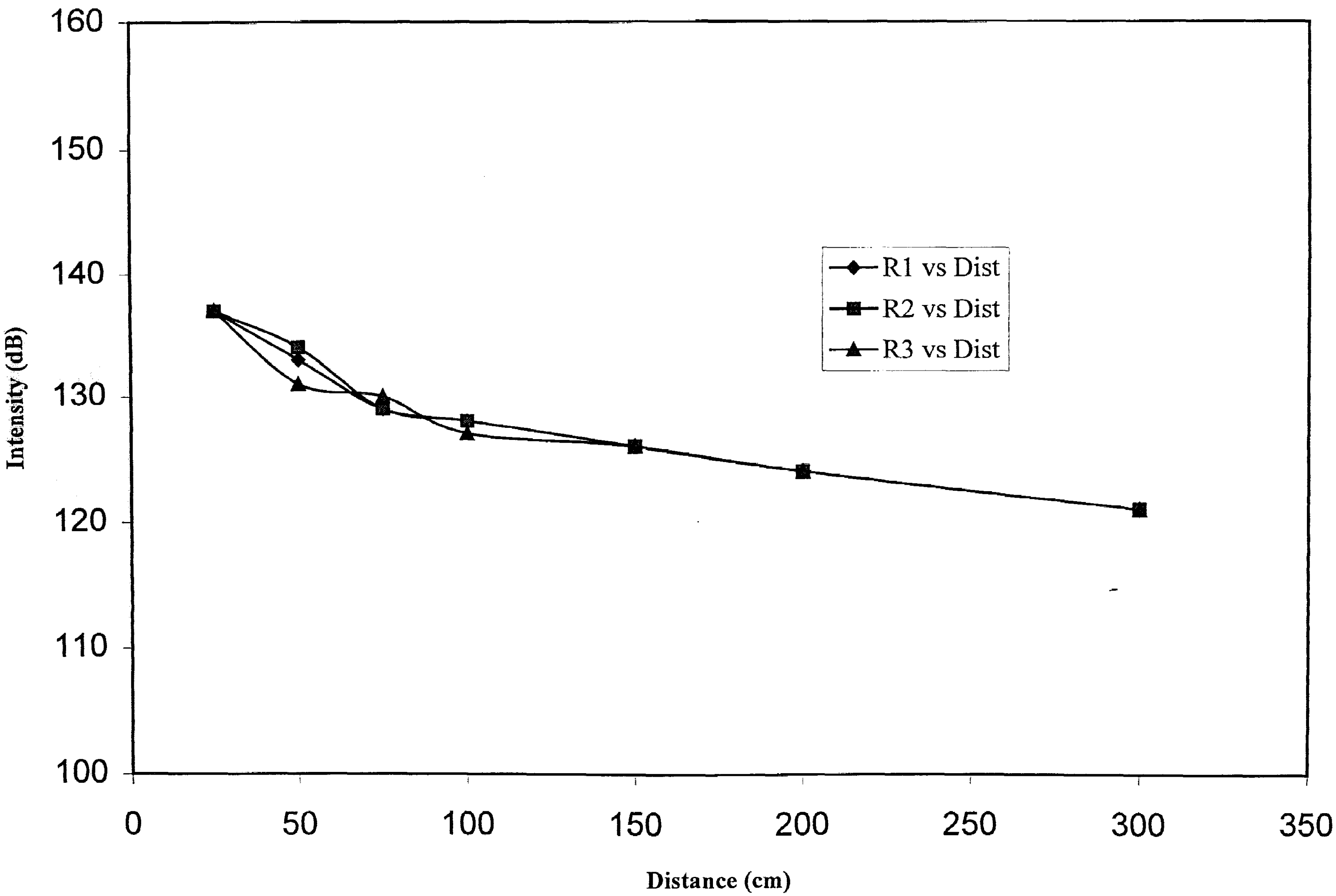


Figure A.27 Plot of Intensity versus Distance at 6.5 scfm with whistle number 5 for Sound Meter

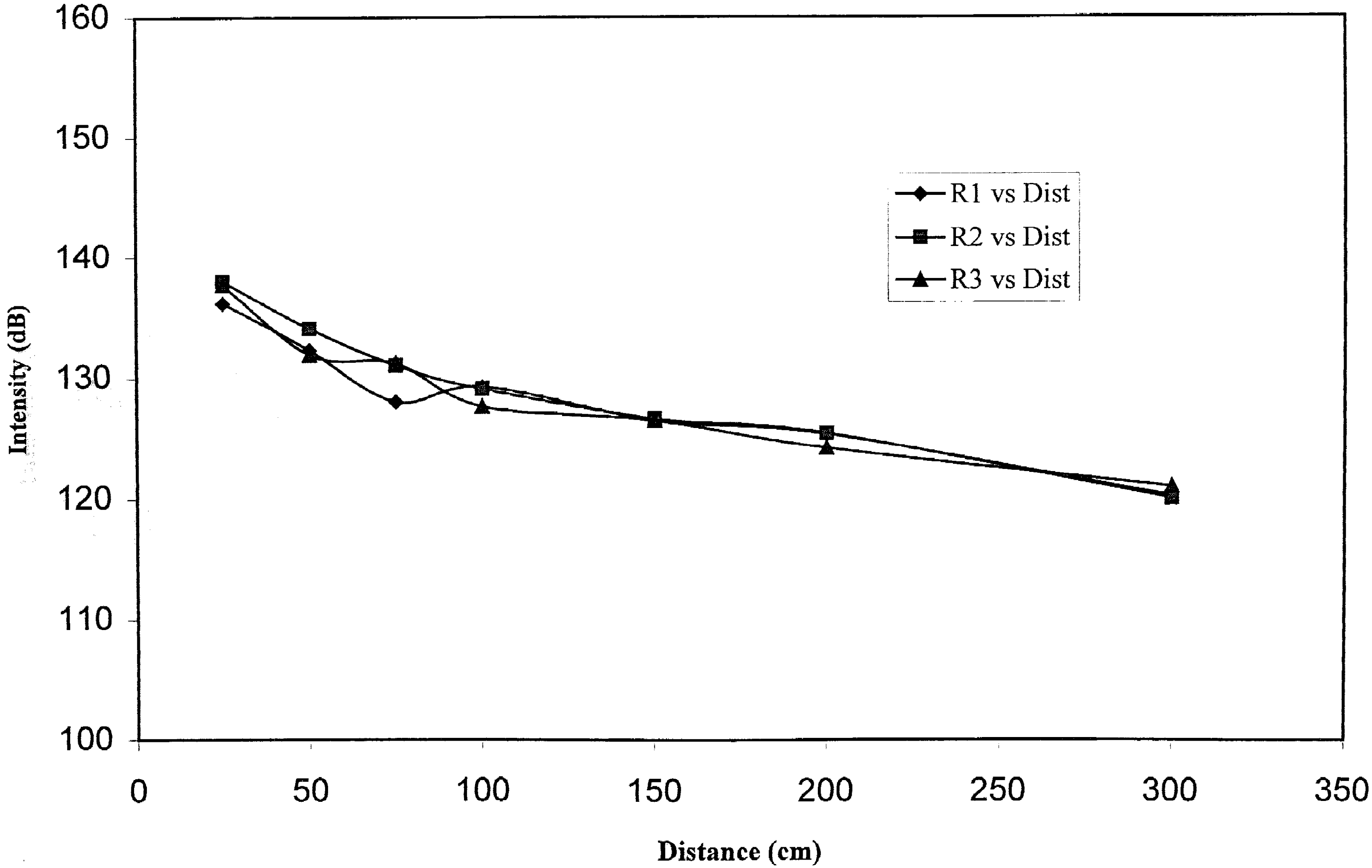


Figure A.28 Plot of Intensity versus Distance at 6.5 scfm with whistle number 5 for Microphone

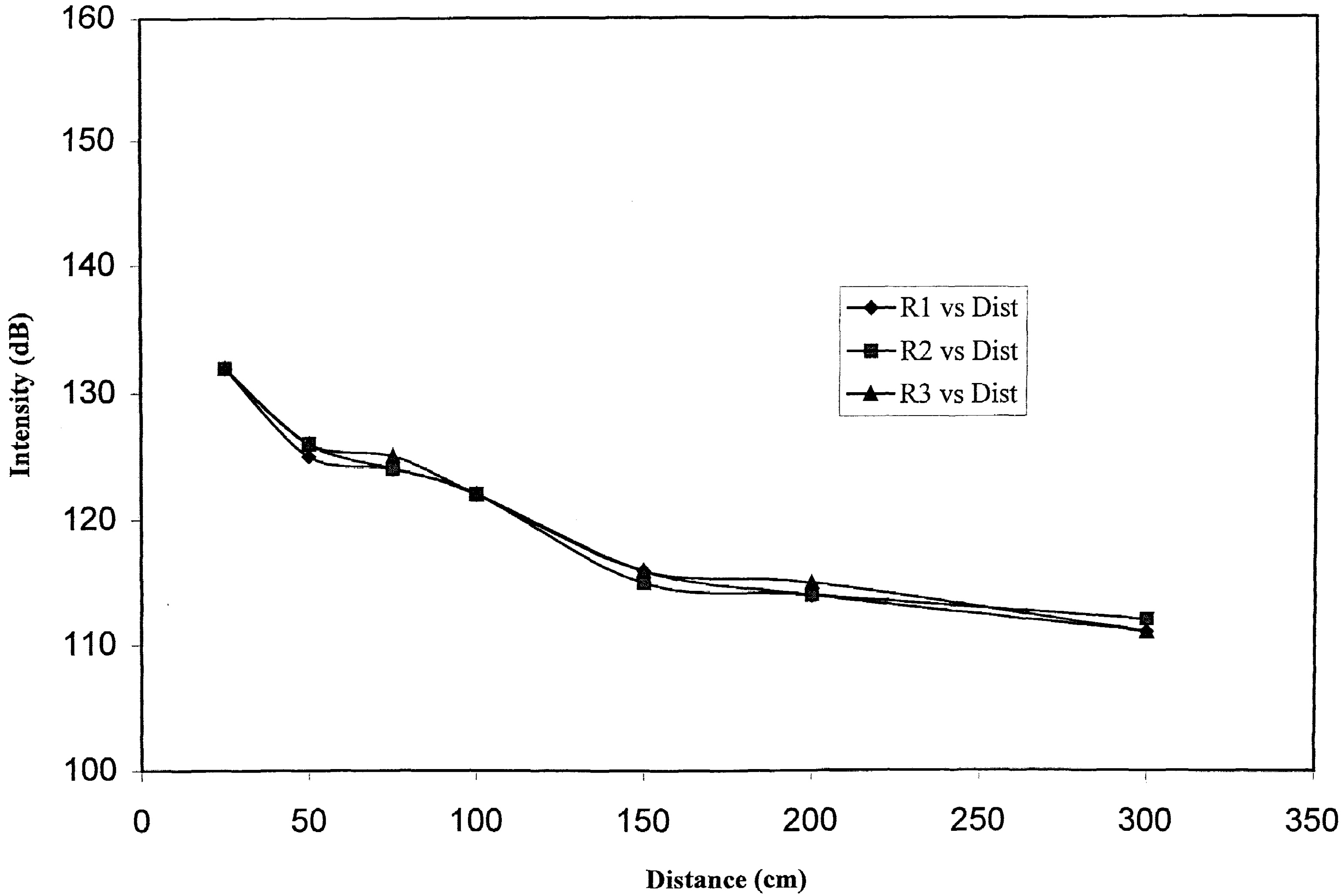


Figure A.29 Plot of Intensity versus Distance at 4.5 scfm with whistle number 5 for Sound Meter

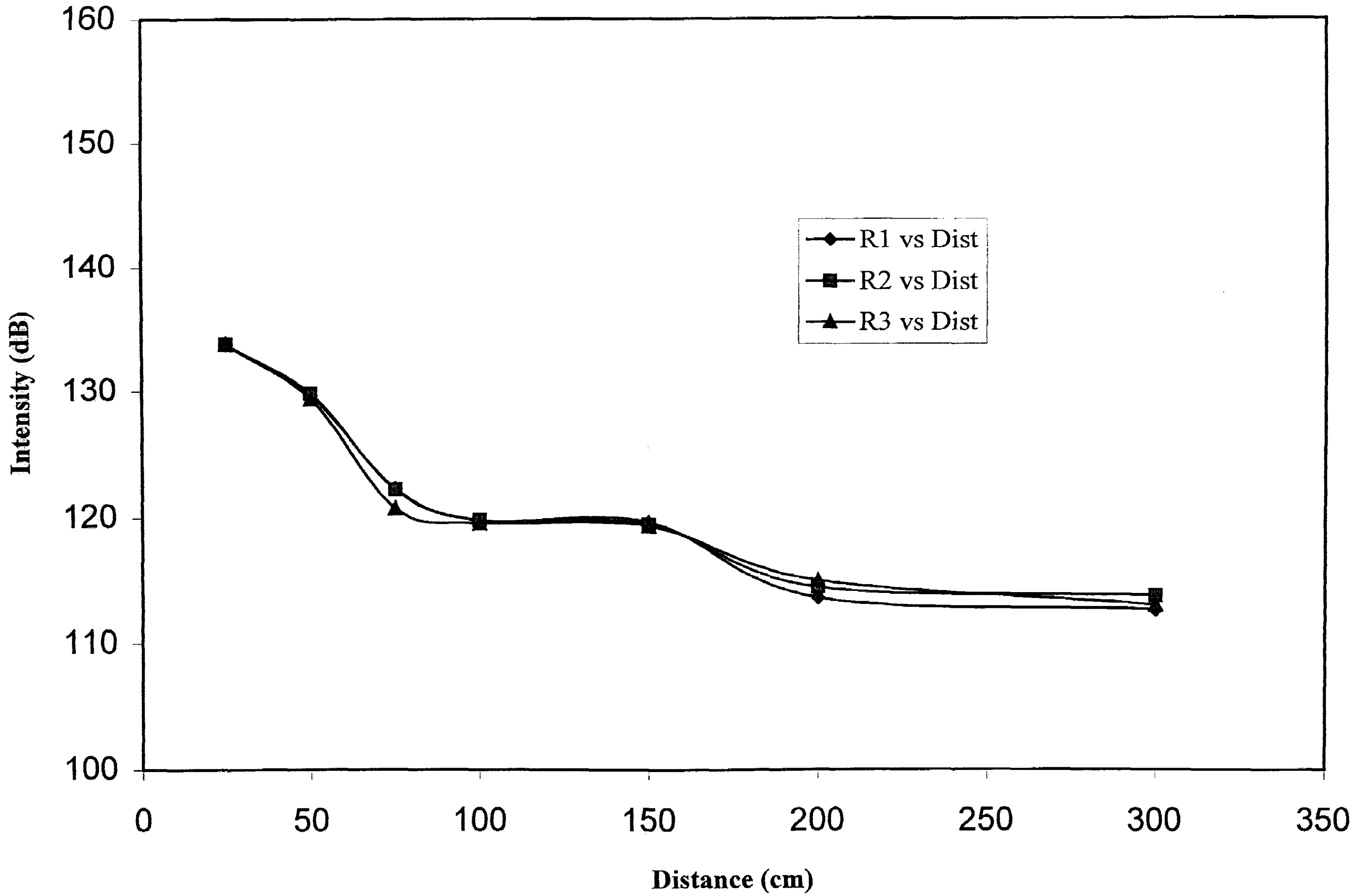


Figure A.30 Plot of Intensity versus Distance at 4.5 scfm with whistle number 5 for Microphone

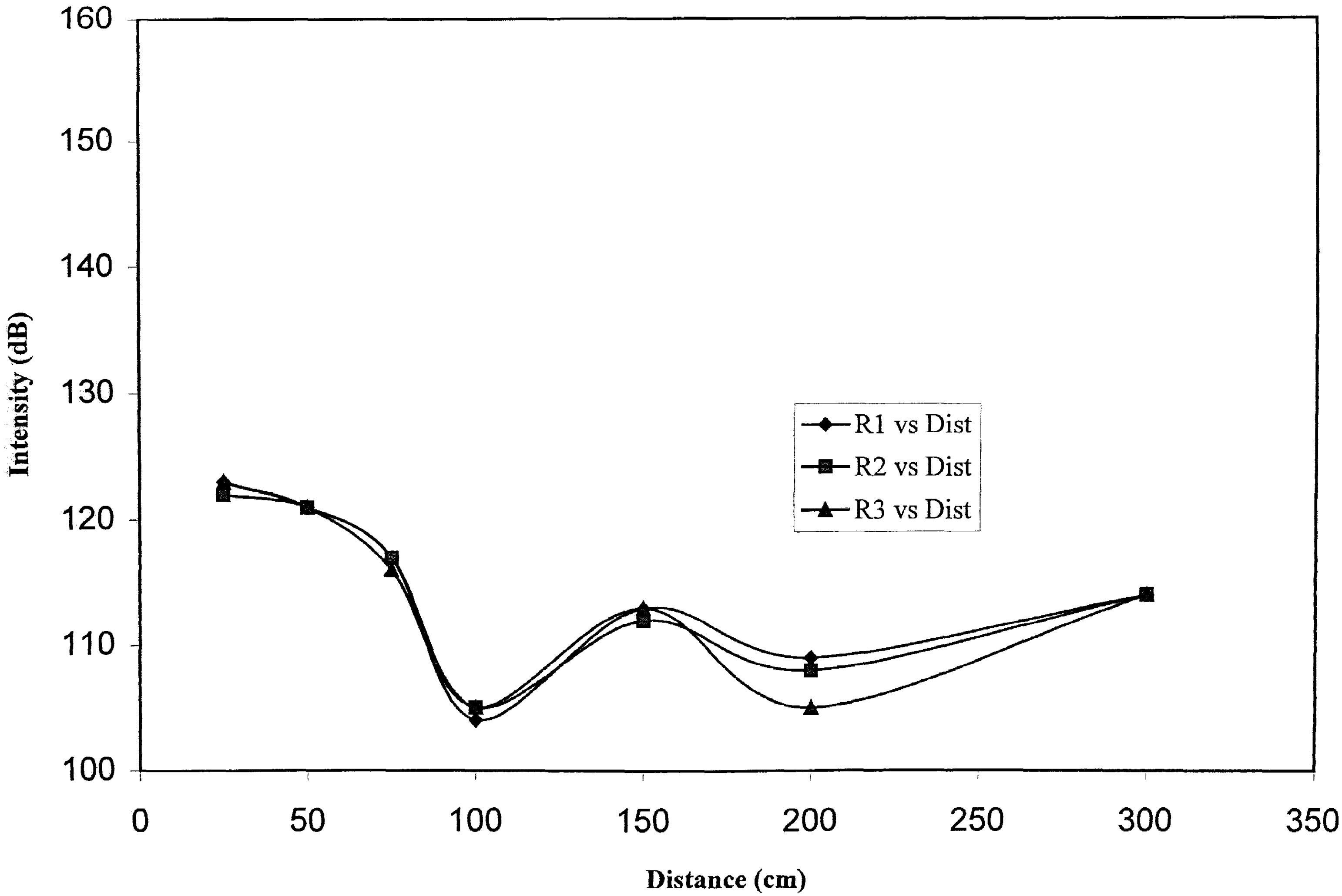


Figure A.31 Plot of Intensity versus Distance at 3.5 scfm with whistle number 5 for Sound Meter

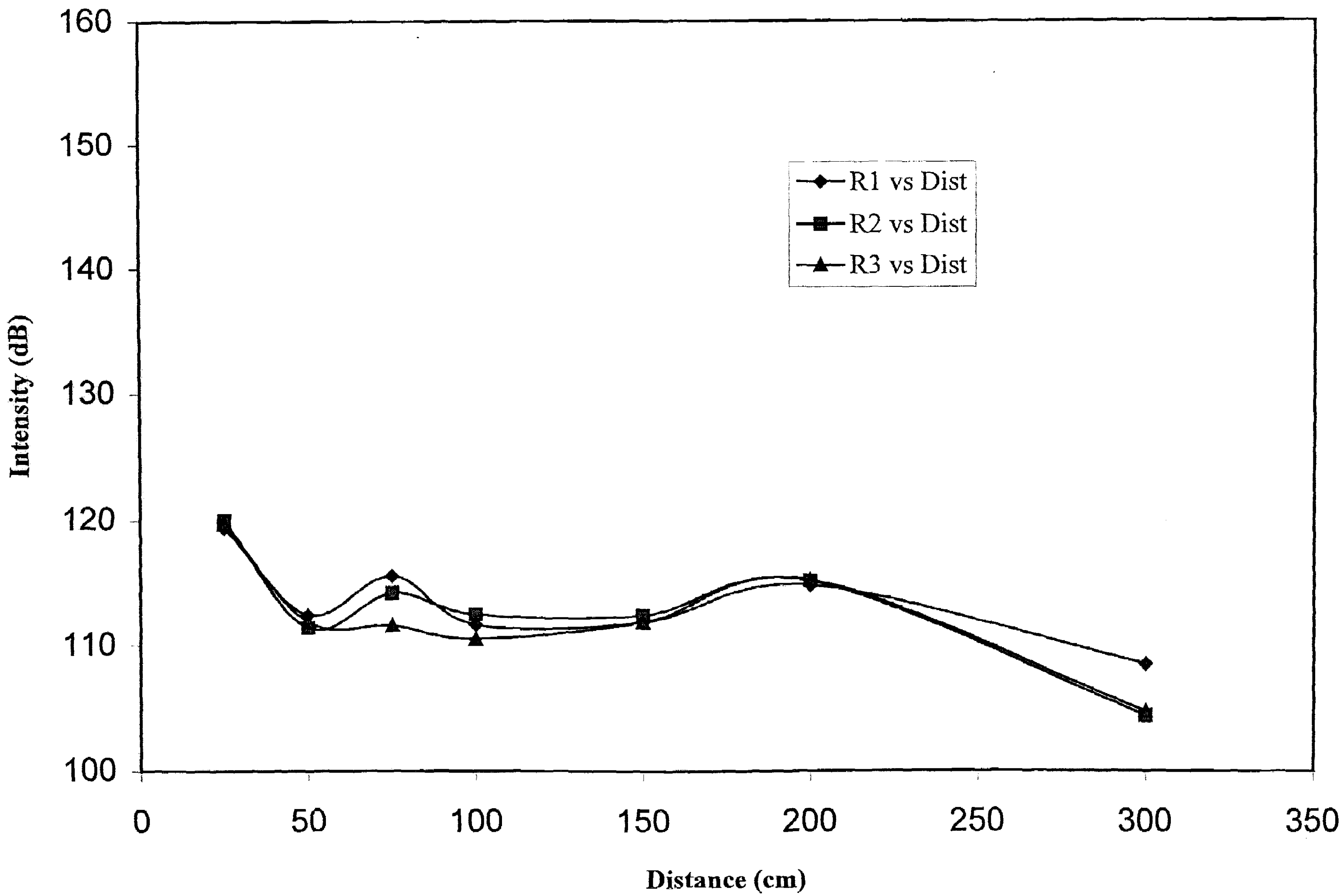


Figure A.32 Plot of Intensity versus Distance at 3.5 scfm with whistle number 5 for Microphone

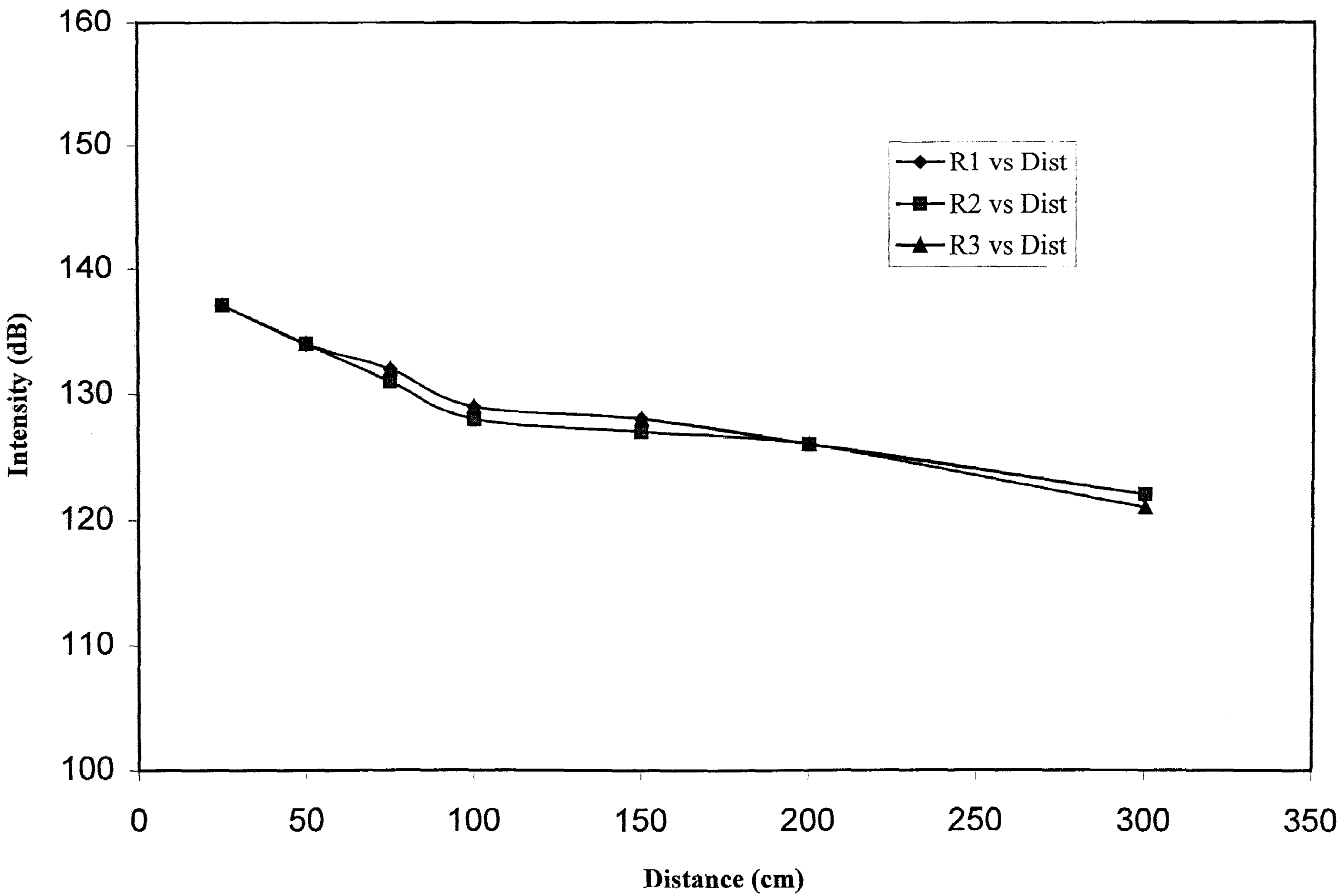


Figure A.33 Plot of Intensity versus Distance at 6.5 scfm with whistle number 5 for Sound Meter (Set 2)

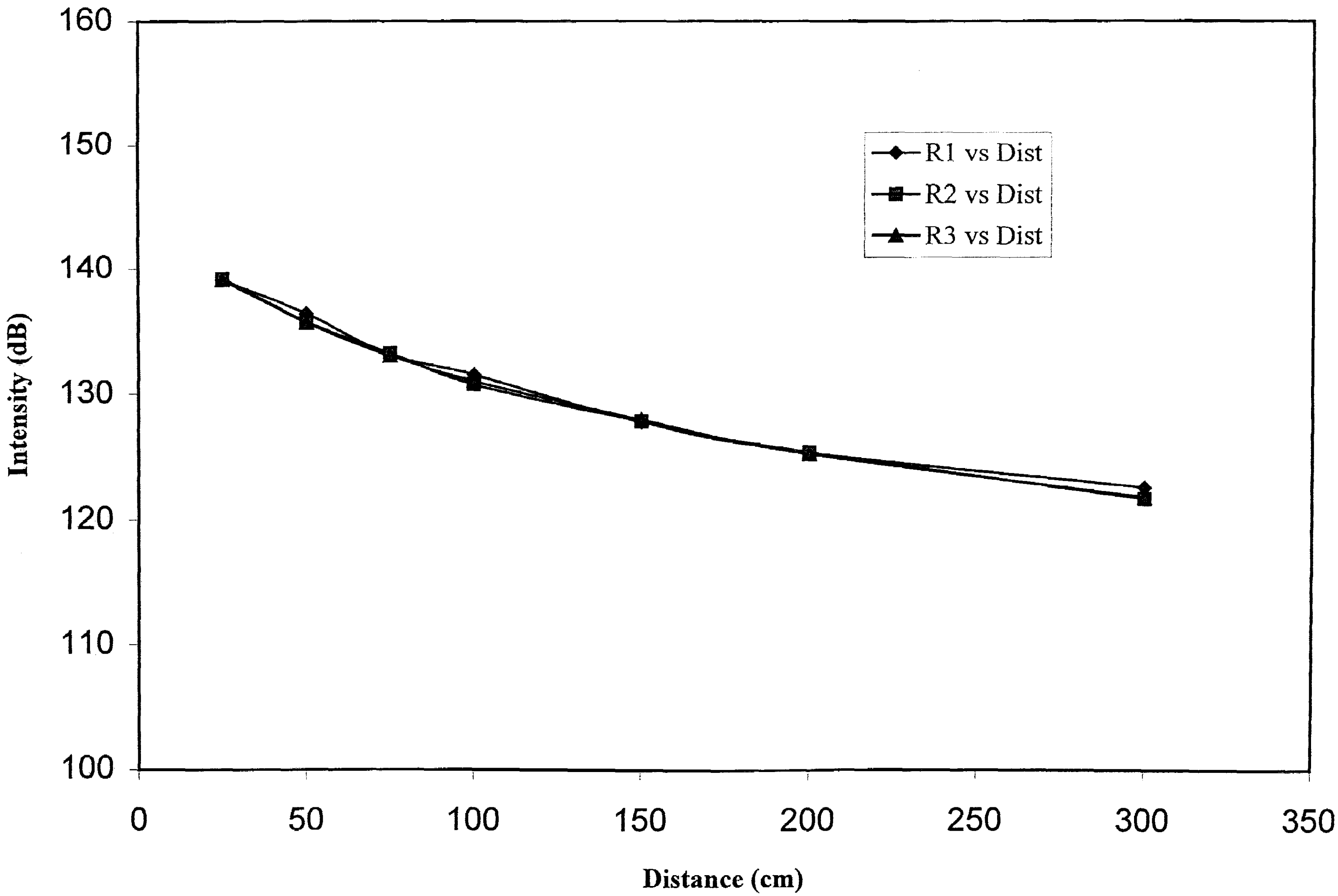


Figure A.34 Plot of Intensity versus Distance at 6.5 scfm with whistle number 5 for Microphone (Set 2)

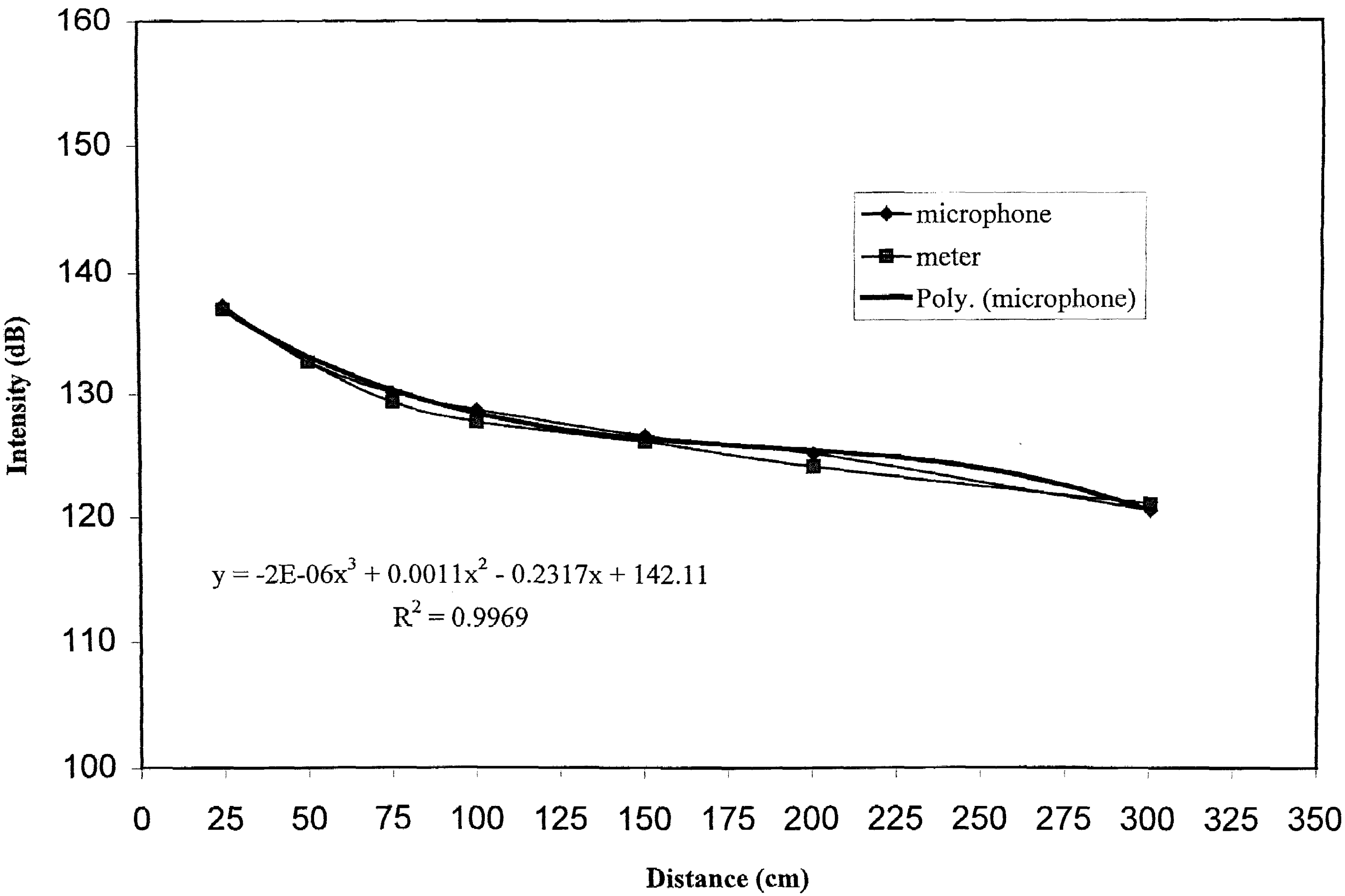


Figure A.35 Comparison Plot of Average Intensity versus Distance at 6.5 scfm with whistle number 5 for Microphone and Sound Meter

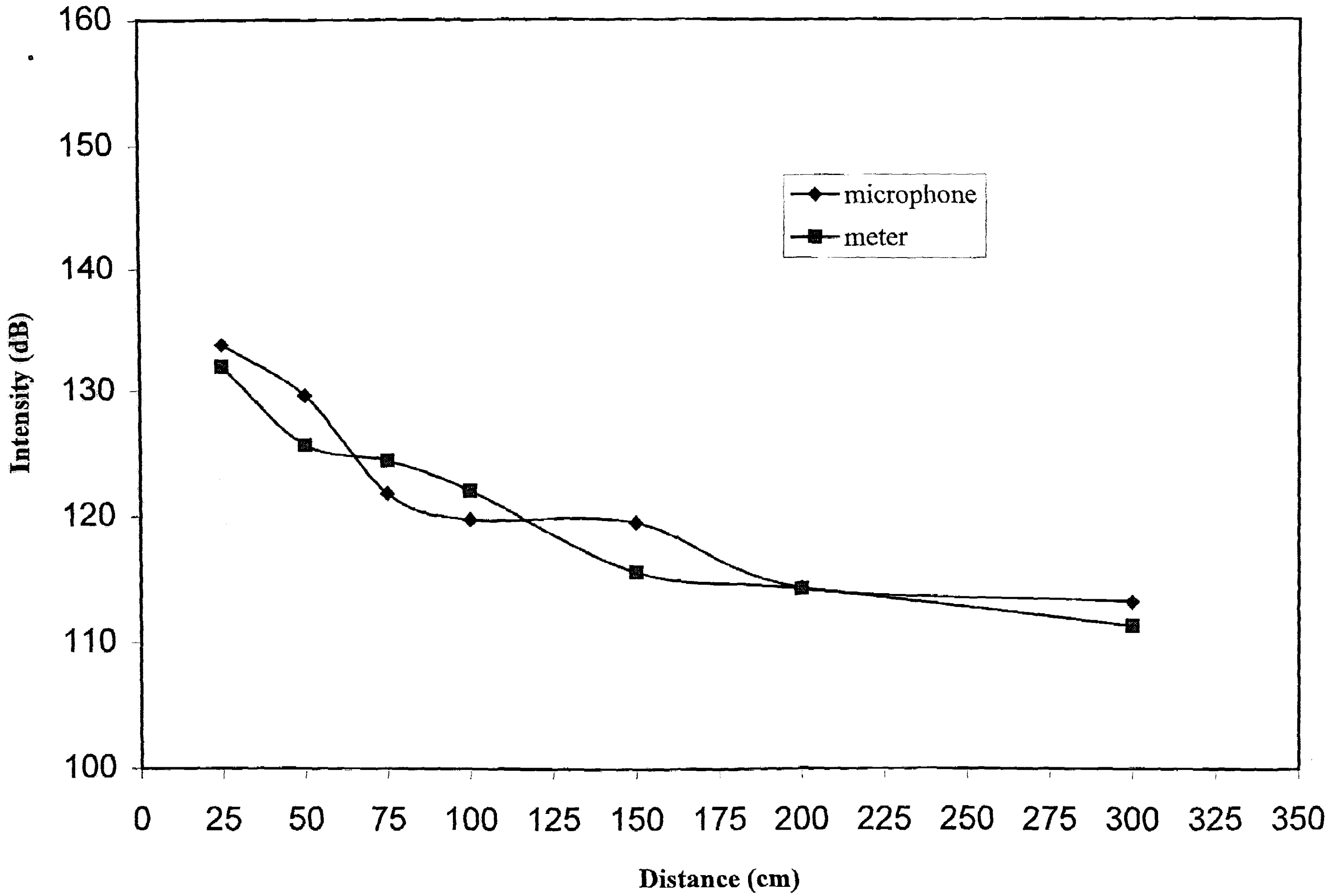


Figure A.36 Comparison Plot of Average Intensity versus Distance at 4.5 scfm with whistle number 5 for Microphone and Sound Meter

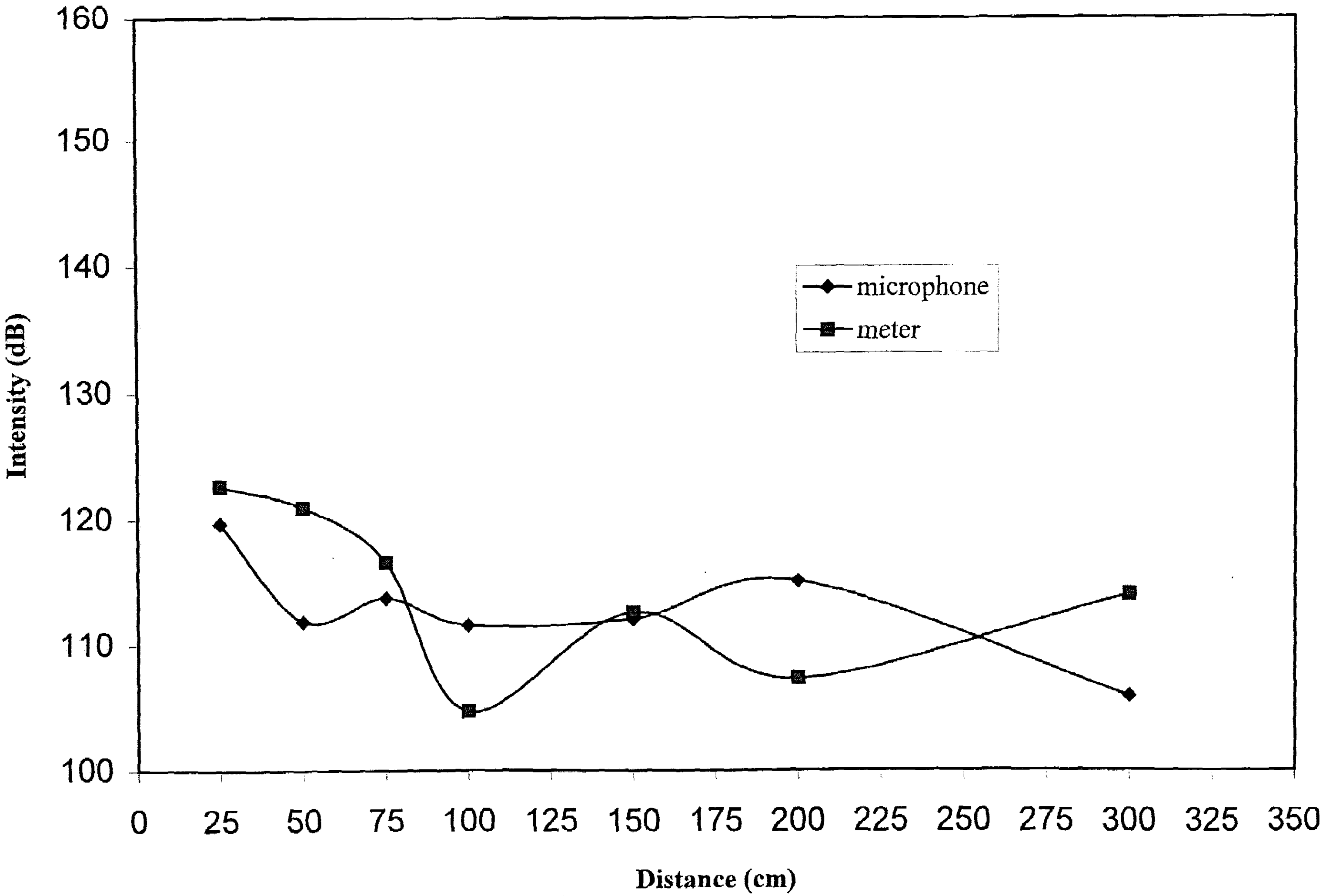


Figure A.37 Comparison Plot of Average Intensity versus Distance at 3.5 scfm with whistle number 5 for Microphone vs Sound Meter

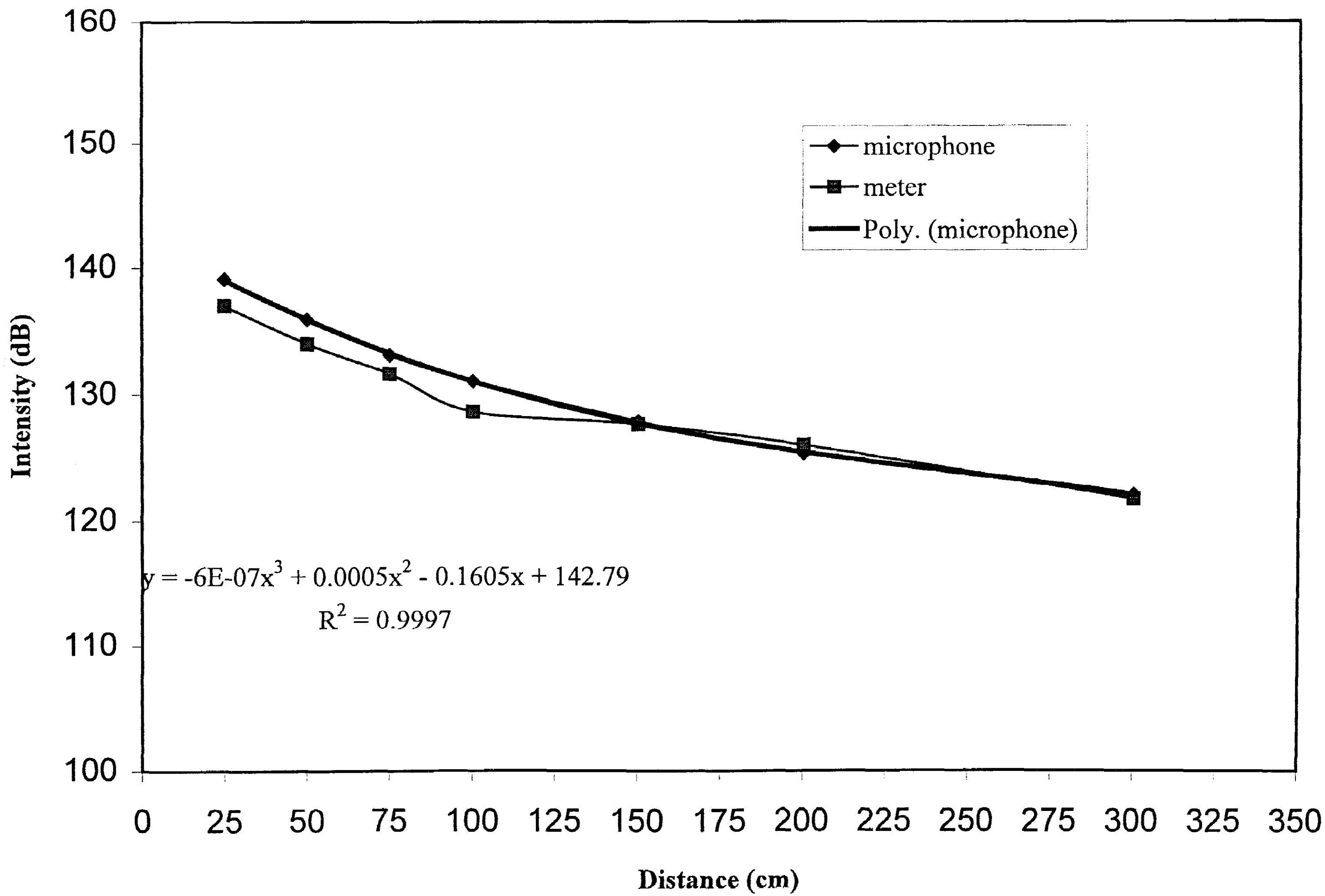


Figure A.38 Comparison Plot of Average Intensity versus Distance at 6.5 scfm with whistle number 5 for Microphone and Sound Meter (Set 2)

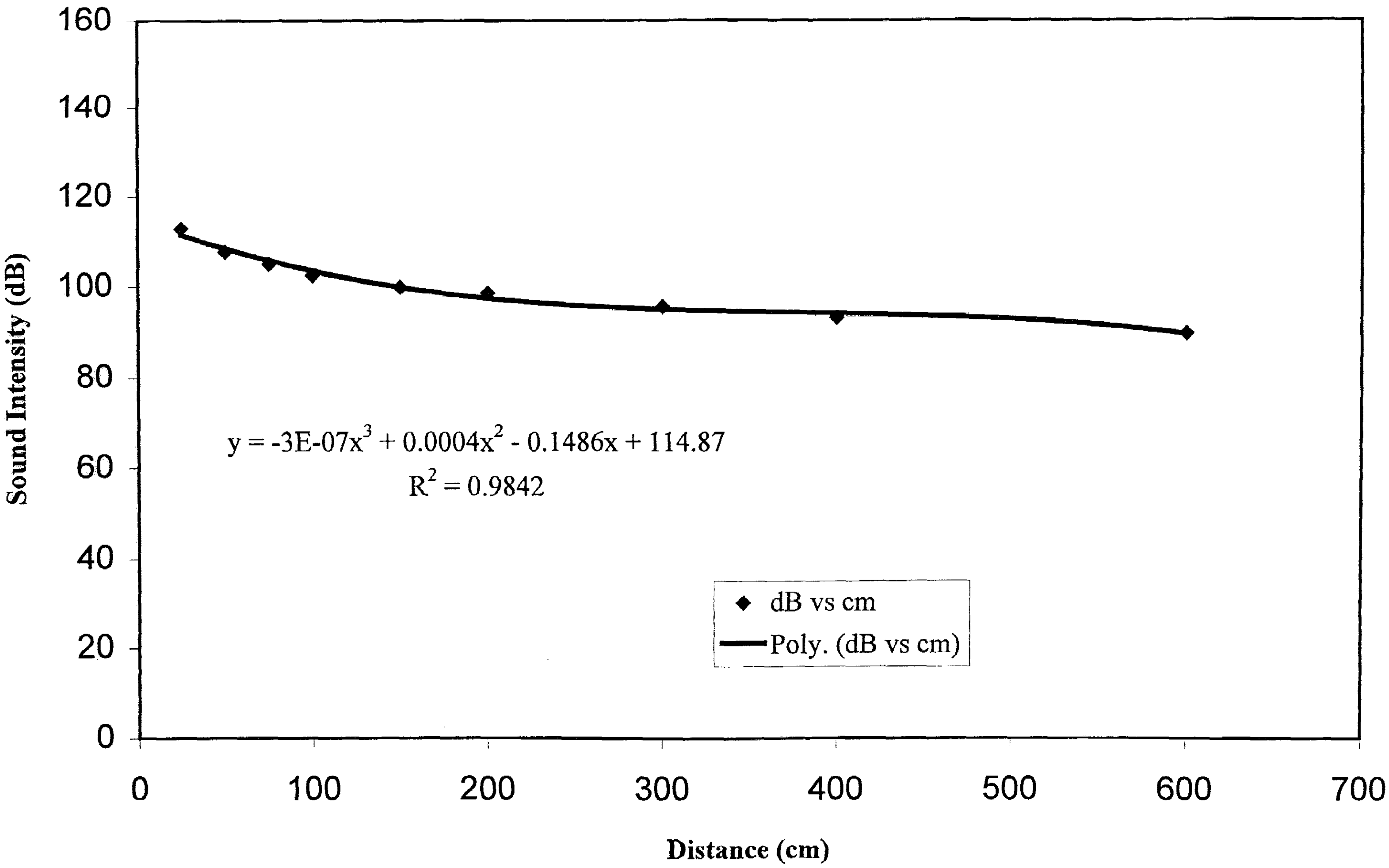


Figure A.39 Plot of Sound Intensity versus Distance at 6.5 scfm for Whistle No. 4

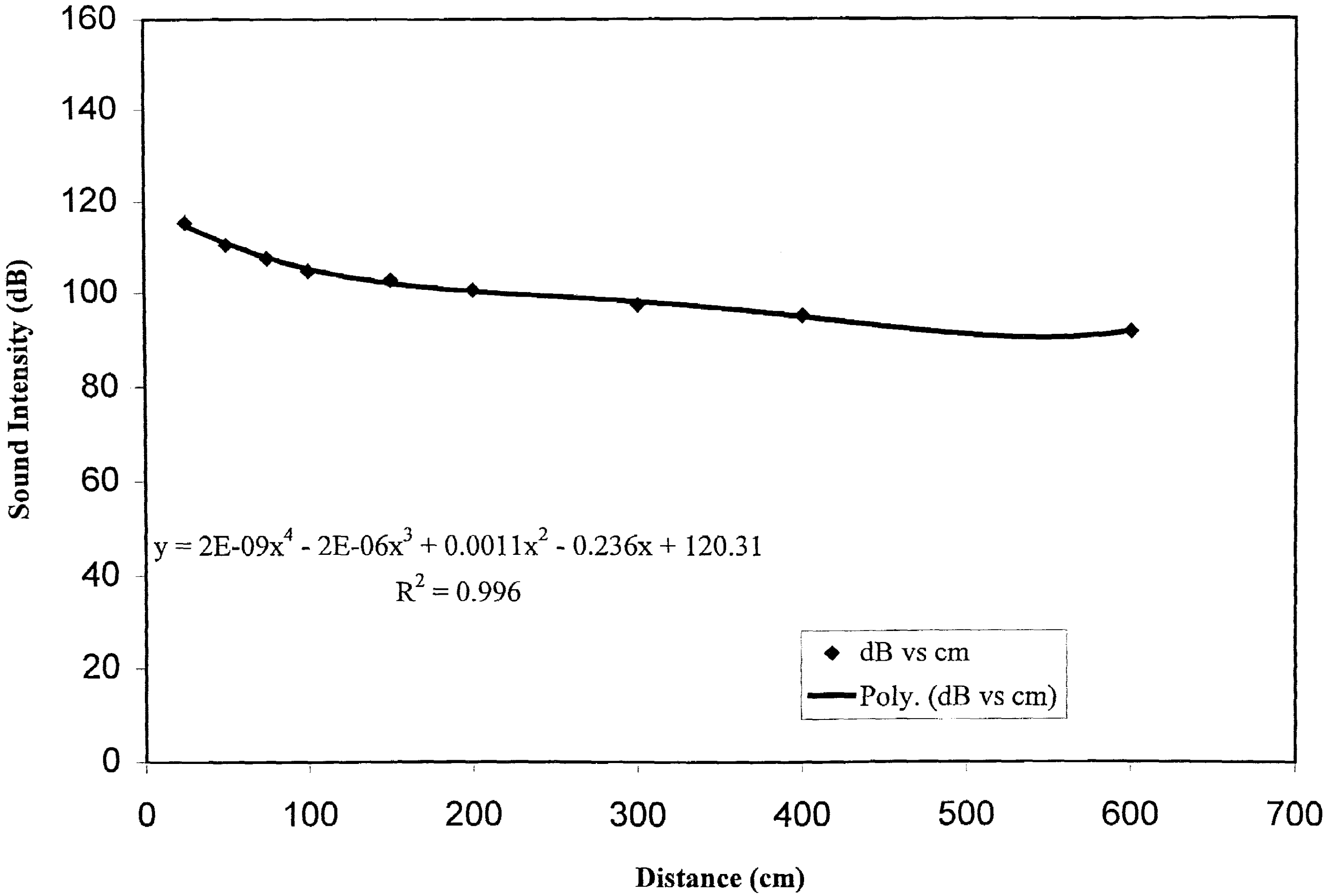


Figure A.40 Plot of Sound Intensity versus Distance at 6.5 scfm for Whistle No. 5

APPENDIX B

SAMPLE CALCULATION

Figure B.1 Screenshot of Cool Edit '96 receiving no signal

Figure B.1 shows the opening view of the Wave Analyzer Software, Cool Edit '96, where it is not recording any signal. The sound wave is recorded by clicking the *Record* button and can be stopped or paused using the *Stop* and *Pause* buttons respectively. The signal received can be played back by clicking the *Play* button or the signal can be zoomed into or out of by clicking the *Zoom* button and/or the *In*, *Out*, or *Full* buttons.

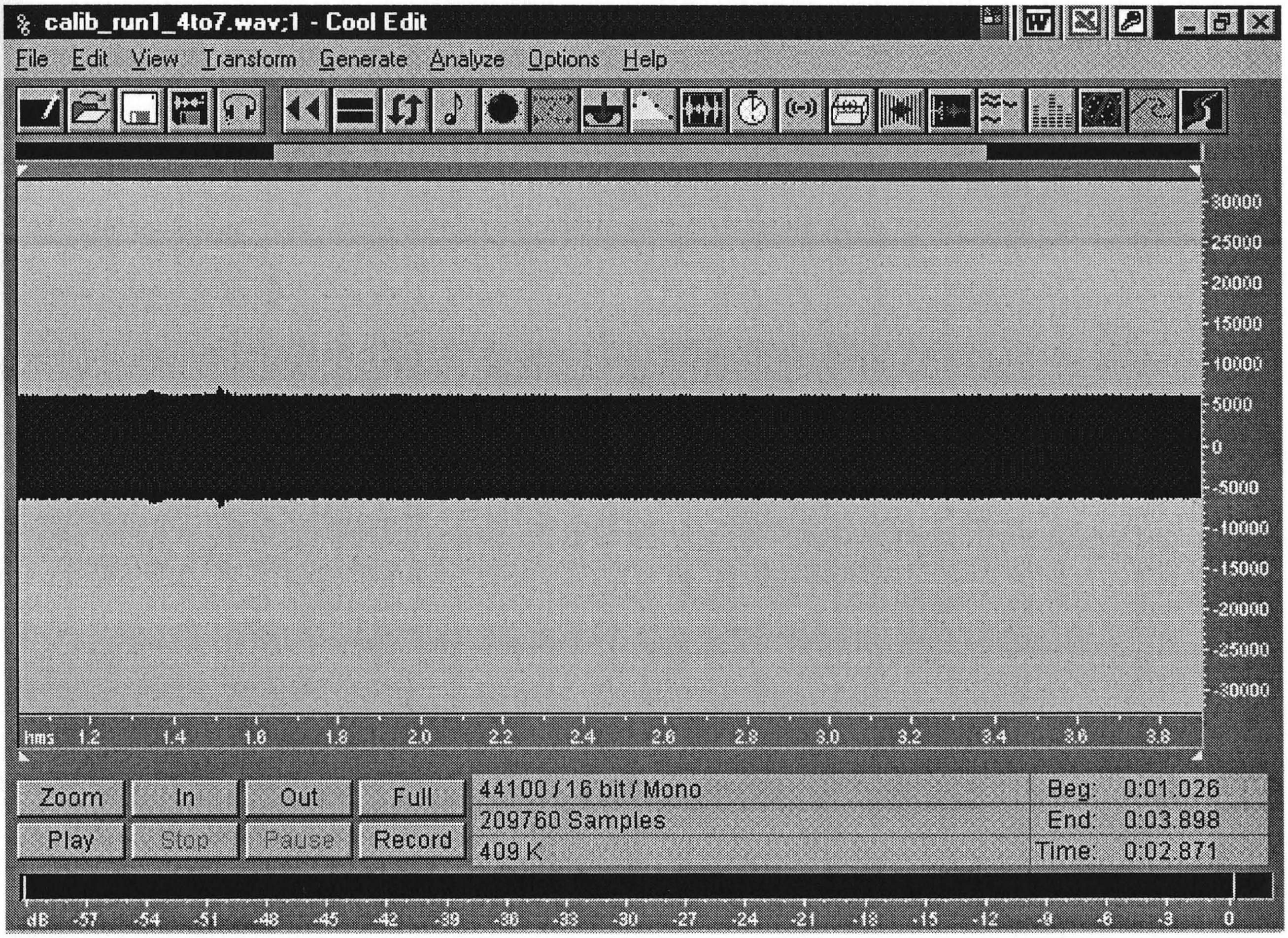


Figure B.2 Screenshot of Cool Edit '96 having recorded the Calibration Signal

Figure B.2 shows the Calibration Signal being recorded by Cool Edit. The Calibration tone is generated by the Pre-amplifier box, which is part of the microphone assembly and which contains the built-in calibrator. The calibration tone is a 94 dB sound wave that is generated at a frequency of 1 kHz.

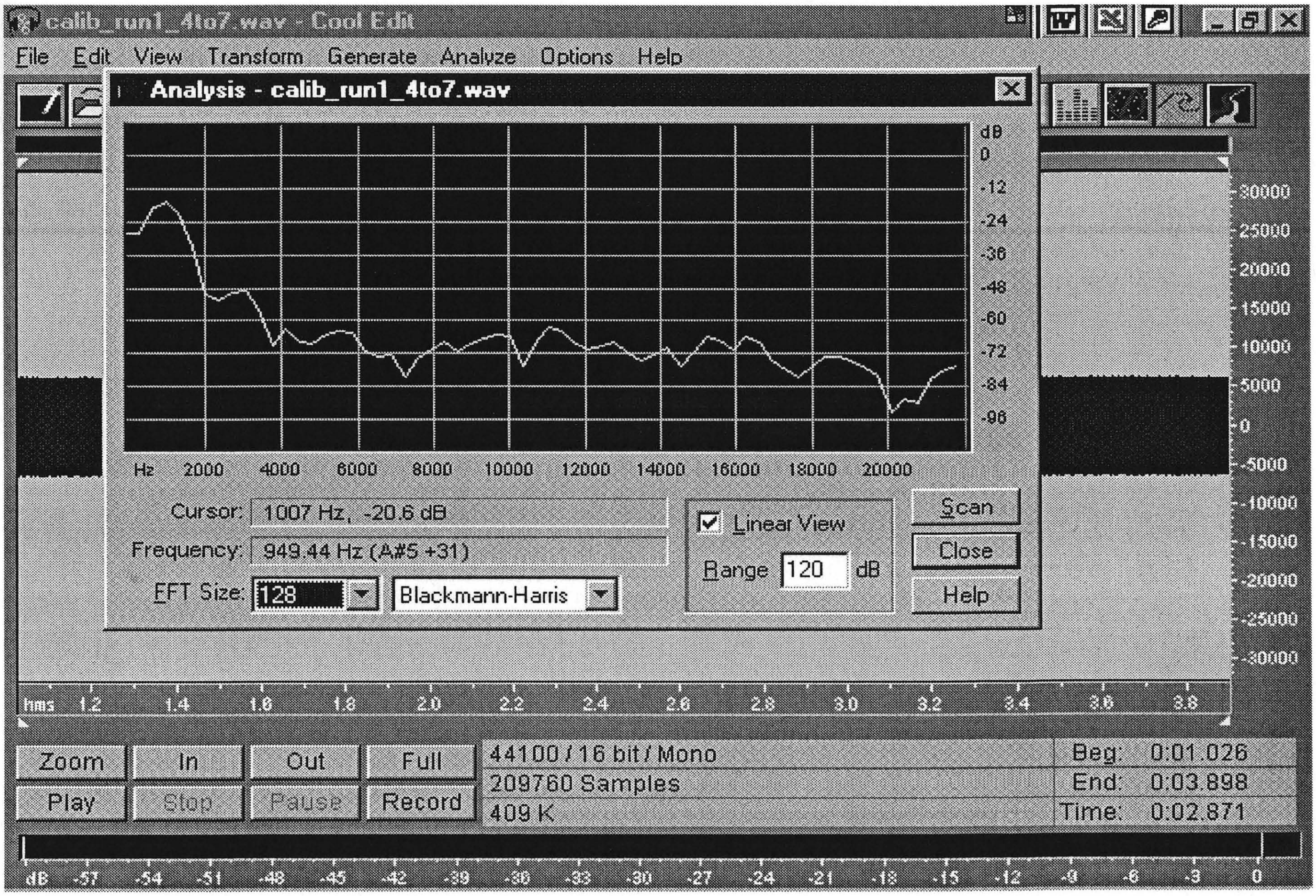


Figure B.3 Screenshot of Cool Edit '96 showing the Frequency Response of the Calibration Signal

Figure B.3 shows the Frequency Response of the Calibration Signal generated by Cool Edit. Since the calibration tone is at a frequency of 1 kHz, as expected, there is a peak in the wave at a frequency of 1000 Hz, which corresponds to the 94 dB calibration tone. The negative scale on the y-axis represents the relative decibel value on the Cool Edit scale. When the peak value of the calibration tone is read off the y-axis negative scale, it gives the relative value of the calibration tone corresponding to the absolute value of 94 dB. This value can be obtained more easily as shown in Figure B.4.

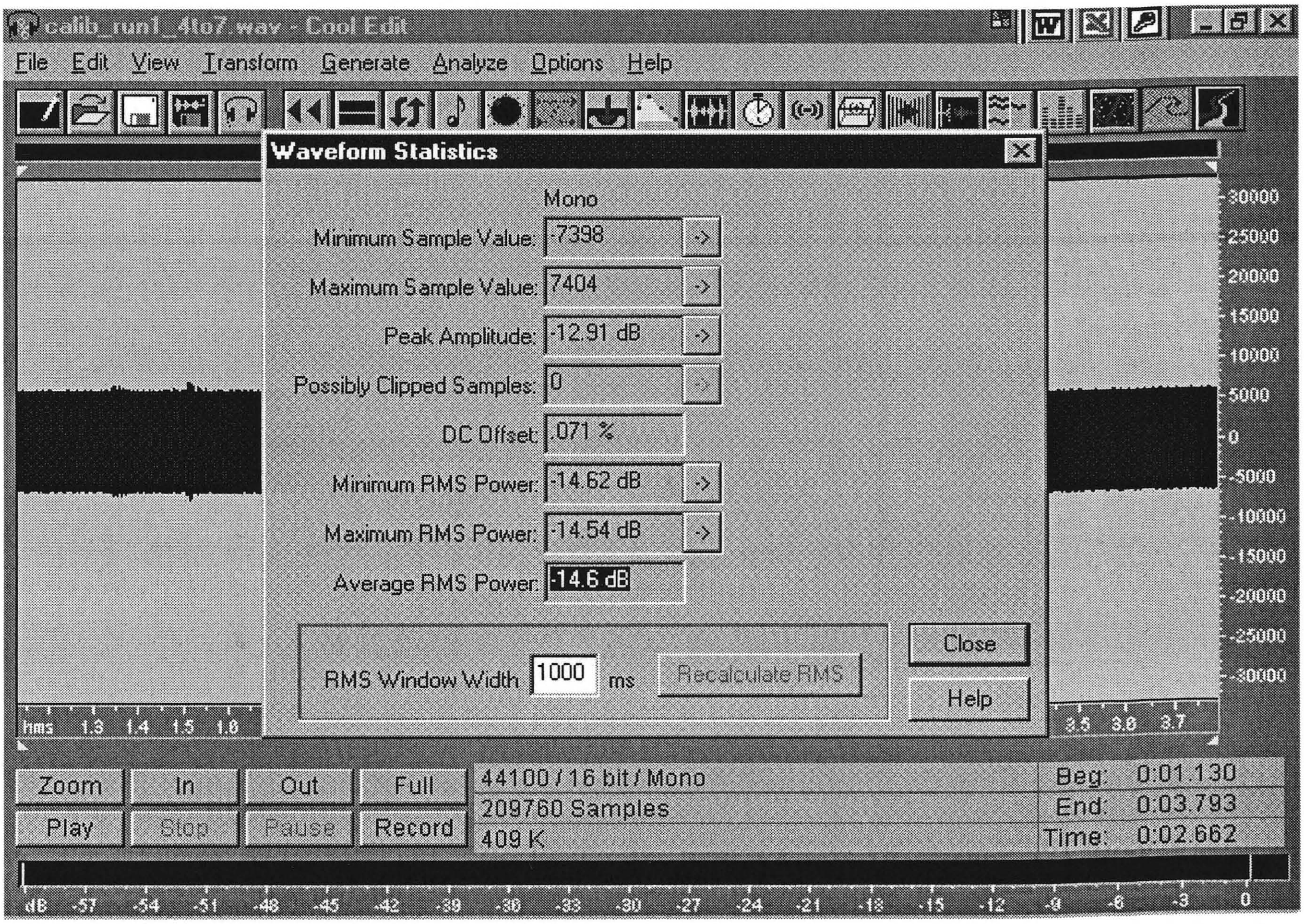


Figure B.4 Screenshot of Cool Edit '96 showing the Statistics of the Calibration Signal

Figure B.4 shows the Statistics of the Calibration Signal generated by Cool Edit. Instead of reading the decibel value of the signal off the y-axis negative scale, a numerical value corresponding to the calibration tone of 94 dB can be obtained by utilizing the Average RMS Power value shown in the above figure, the only difference being that an average value of the intensity is obtained over the wave shown. This value is added to the absolute value of the calibration tone to give the relative value of the calibration tone corresponding to the "0" value on the y-axis scale in Figure B.3.

That is, $94 \text{ dB} \equiv -14.6 \text{ dB}$

Therefore, $0 \text{ dB} \equiv 94 + 14.6 = 108.6 \text{ dB}$

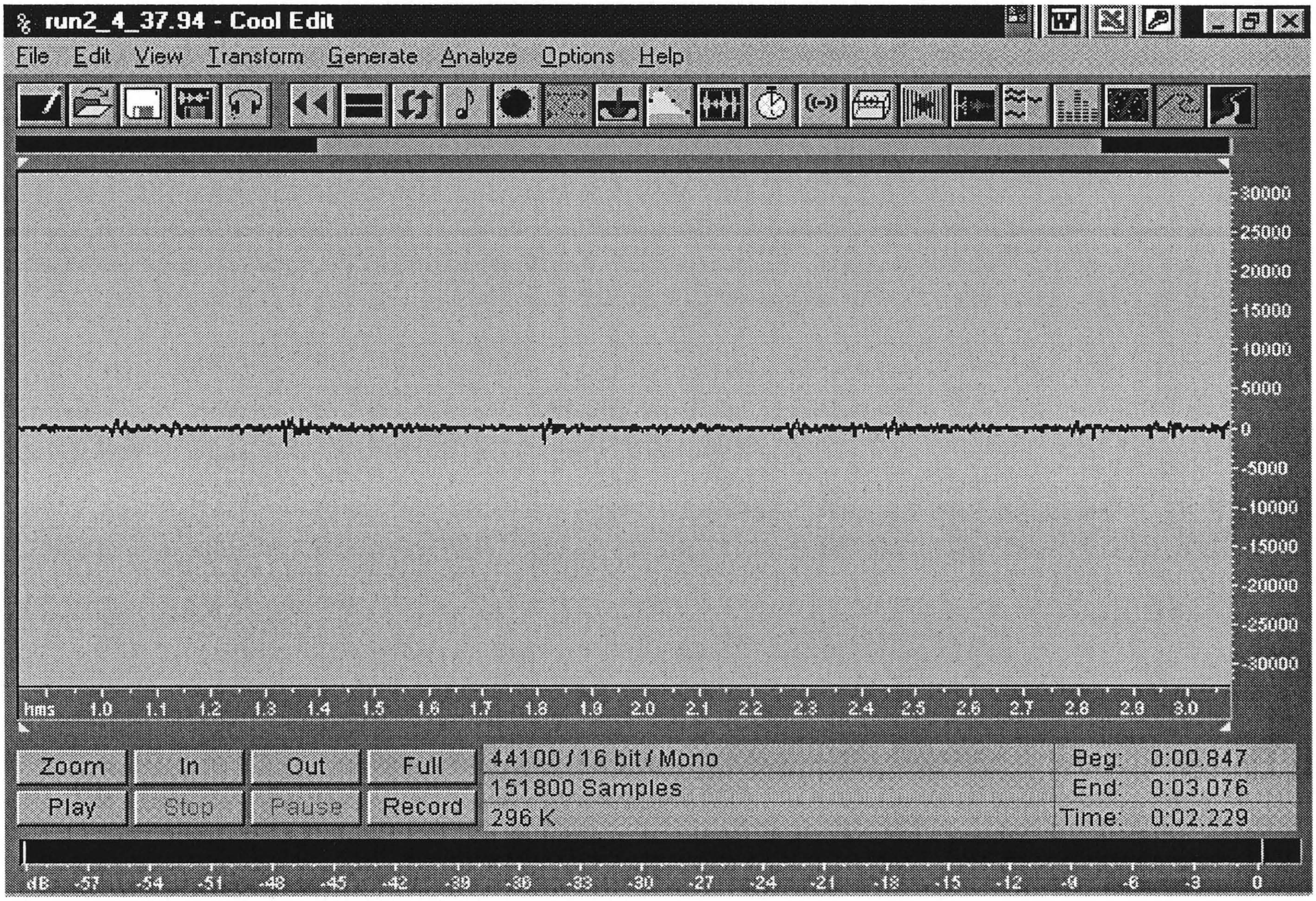


Figure B.5 Screenshot of Cool Edit '96 having recorded a sample signal.

Figure B.5 shows a sample wave recorded by Cool Edit. The sample signal corresponds to Reading 3 obtained under Condition 4 in Table 5.12, which has an absolute intensity value of 70.66 dB. This wave is recorded by selecting an arbitrary time interval and clicking the Record button.

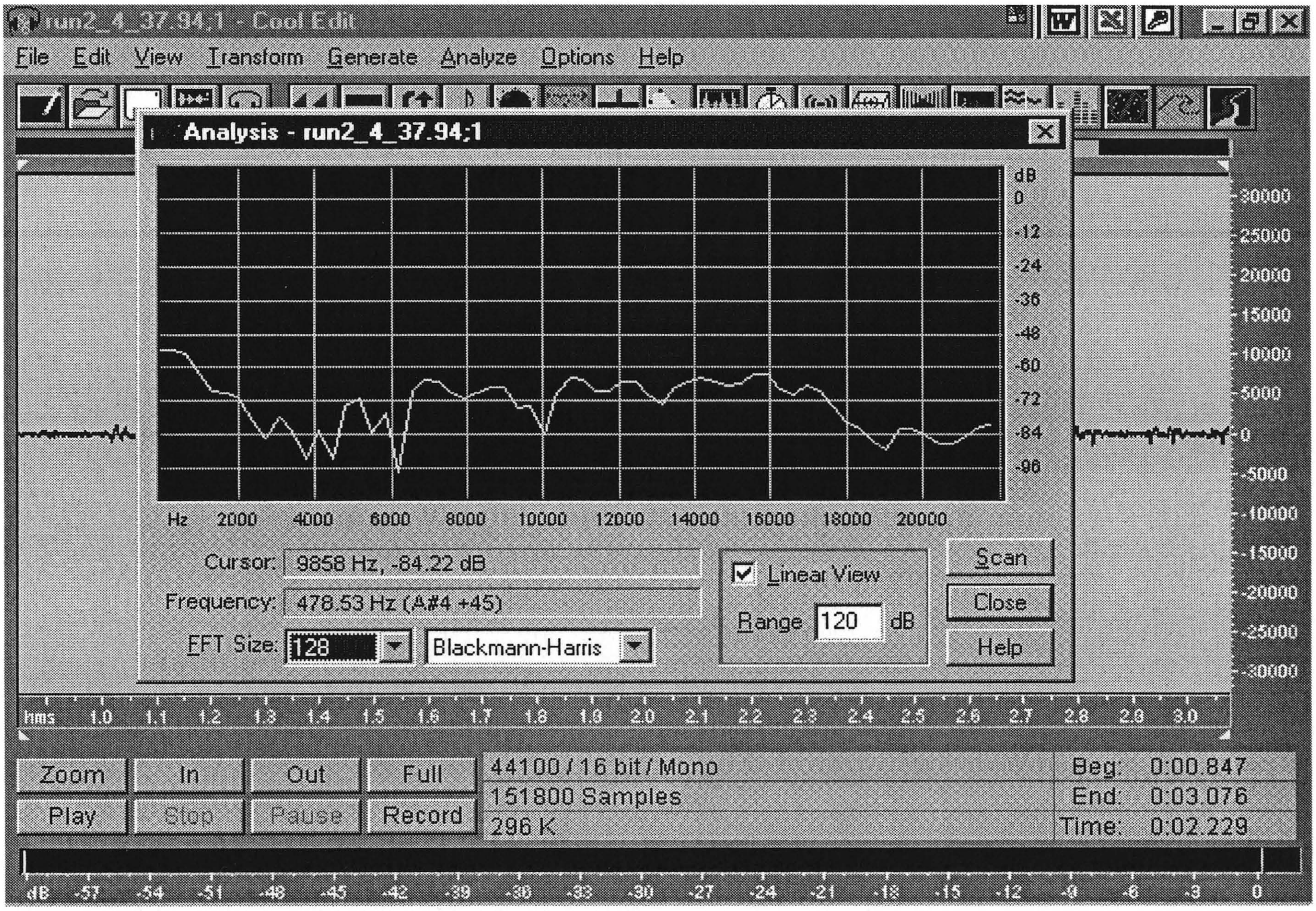


Figure B.6 Screenshot of Cool Edit '96 showing the Frequency Response for the sample signal.

Figure B.6 shows the Frequency Response generated by Cool Edit for the sample wave recorded. Although the whistle generated sonic energy at a frequency of 11 kHz, the signal recorded does not show any significant peak at this frequency, which indicates and reiterates the point that the sound is being absorbed in the fracture before it reaches the microphone. Hence, the signal recorded by the microphone is mostly ambient noise. A filter cannot be used to filter out the lower frequencies since the calibration tone would be offset by the filtering which would alter the final value obtained.

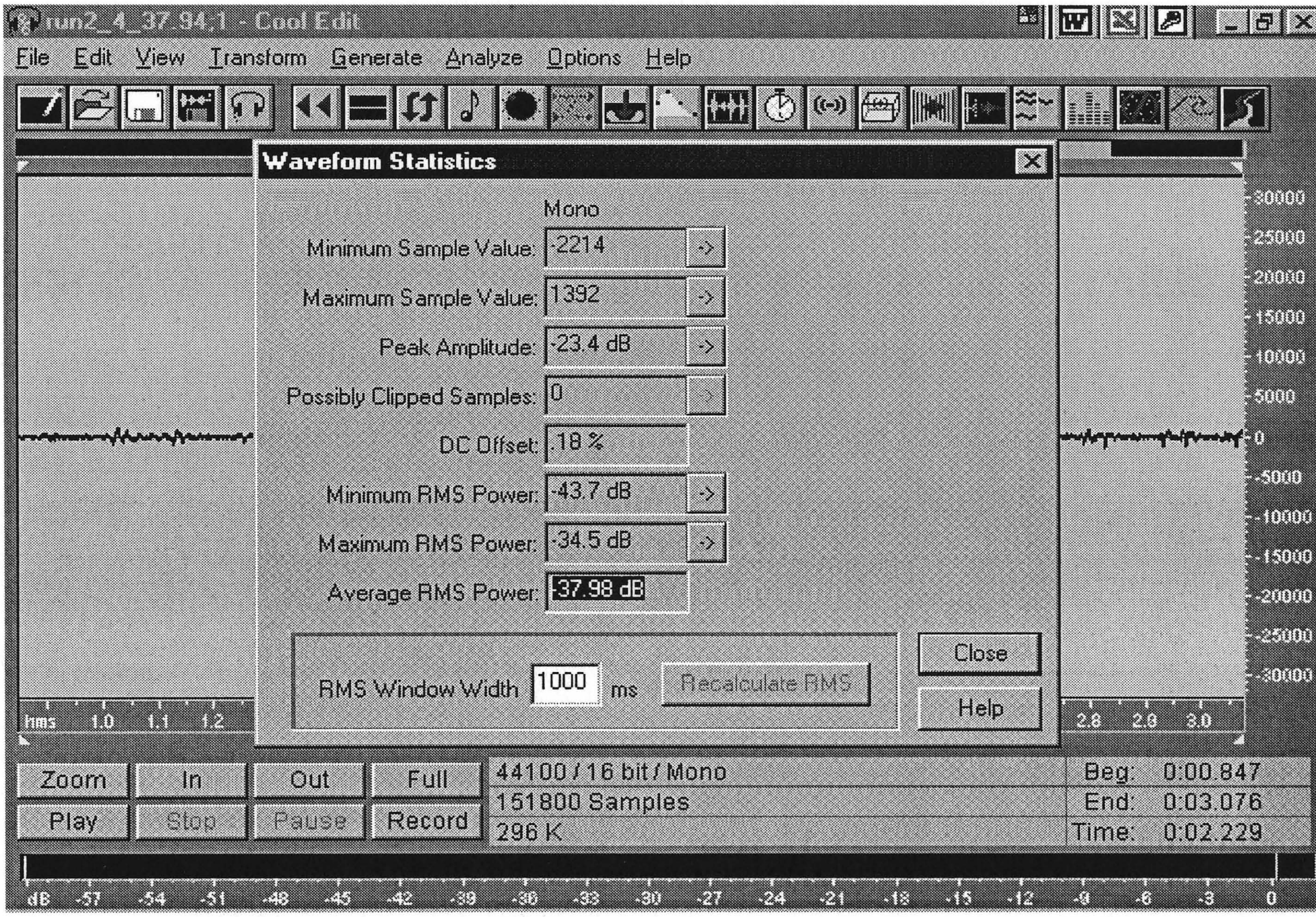


Figure B.7 Screenshot of Cool Edit '96 showing the Statistics for the sample signal.

Figure B.7 shows the Statistics generated by Cool Edit for the sample wave recorded. The Average RMS Power shows a value of –37.98 dB. When this value is added to (or the mathematical absolute value is subtracted from) the calibration value obtained from Figure B.4, the absolute value of the average intensity of the sound wave is obtained.

That is,

Absolute intensity value of signal	=	108.6 – 37.98
	=	70.62 dB

This value is the same as the value given by Reading 3 under Condition 4 in Table 5.12. This is the method by which the values of the intensity for the various experimental

APPENDIX C

DIAGRAMS AND PICTURES

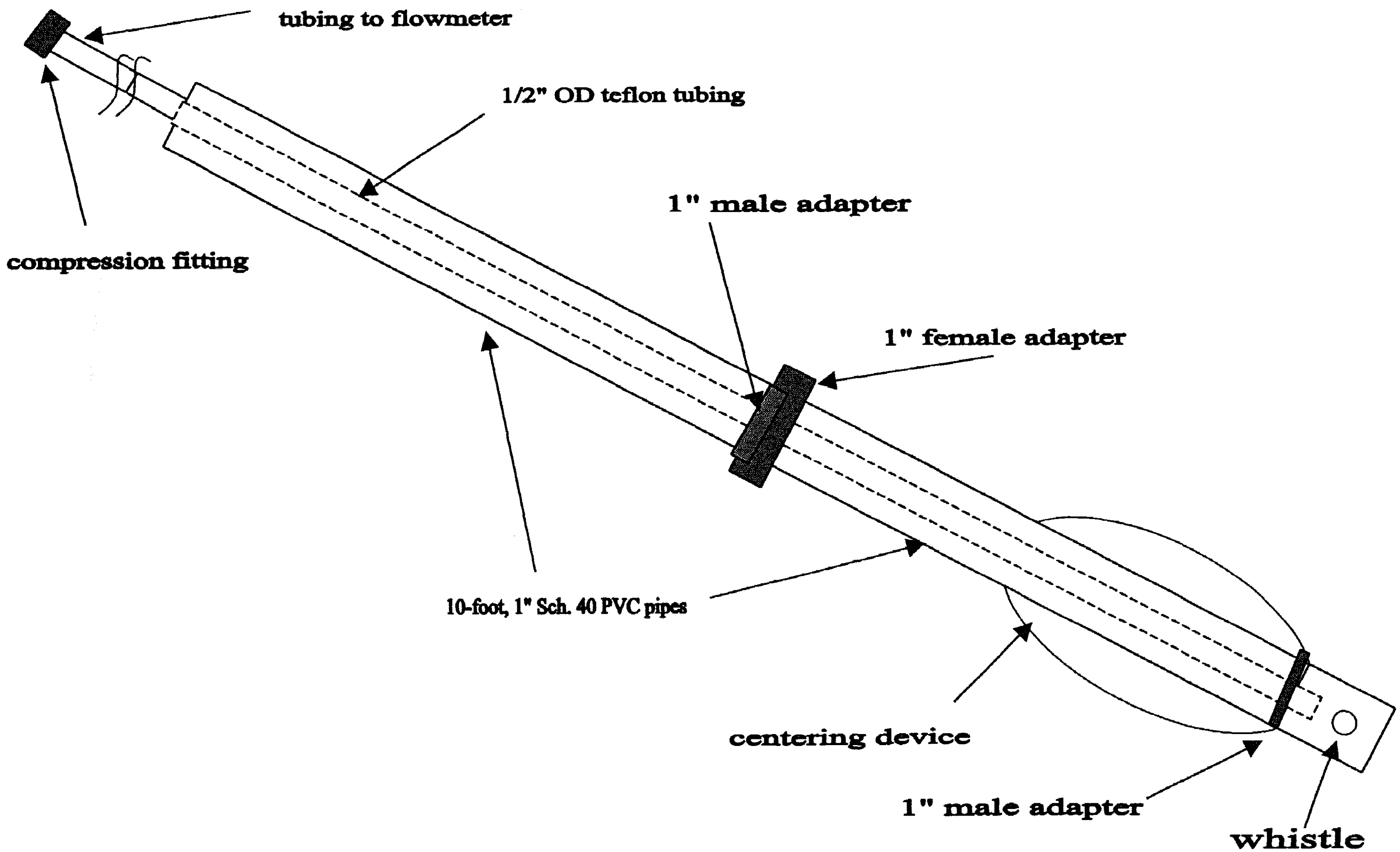


Figure C.1 Injection Well Setup

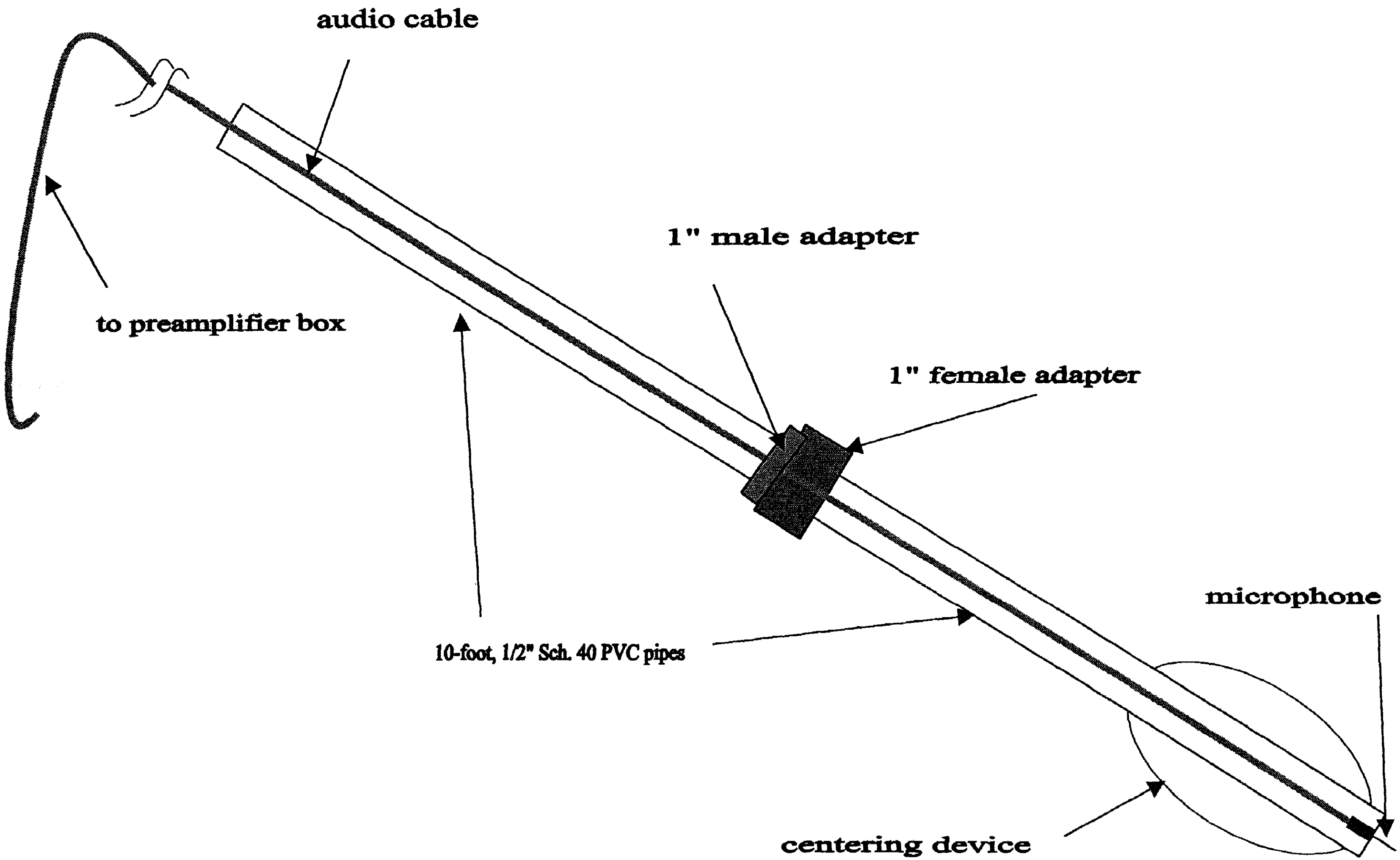


Figure C.2 Extraction well setup

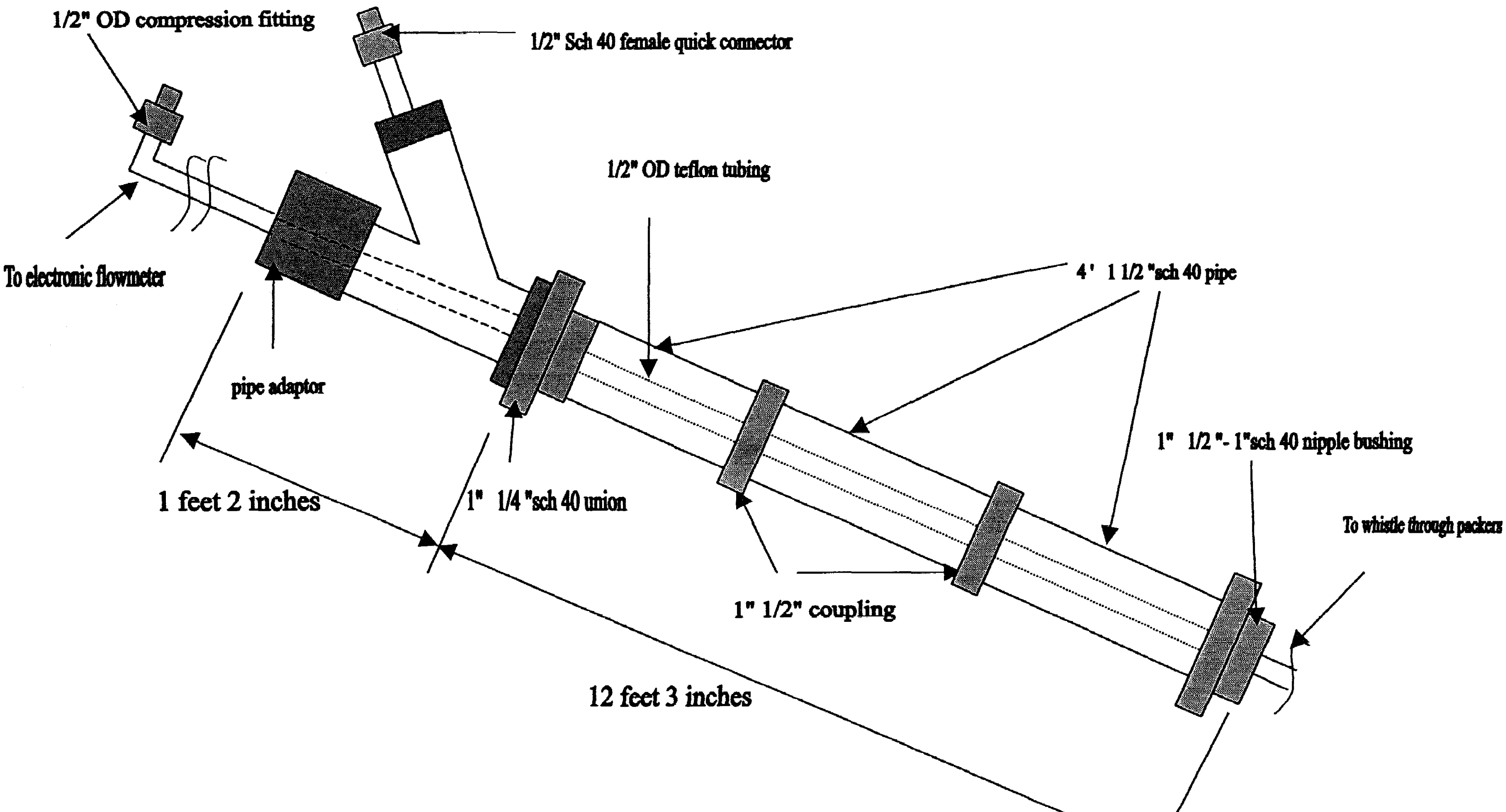


Figure C. 3 Injection Well Setup for Base Value experiments

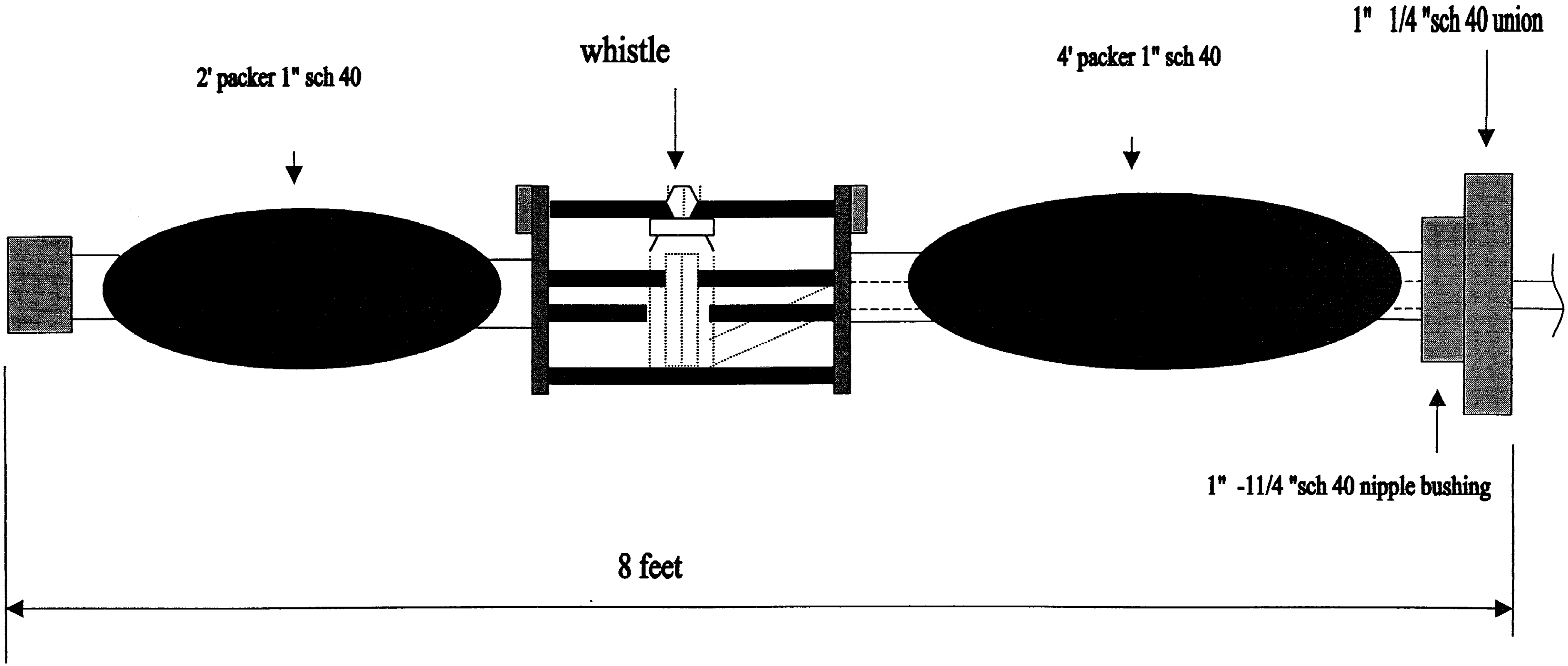


Figure C.4 Packers with whistle

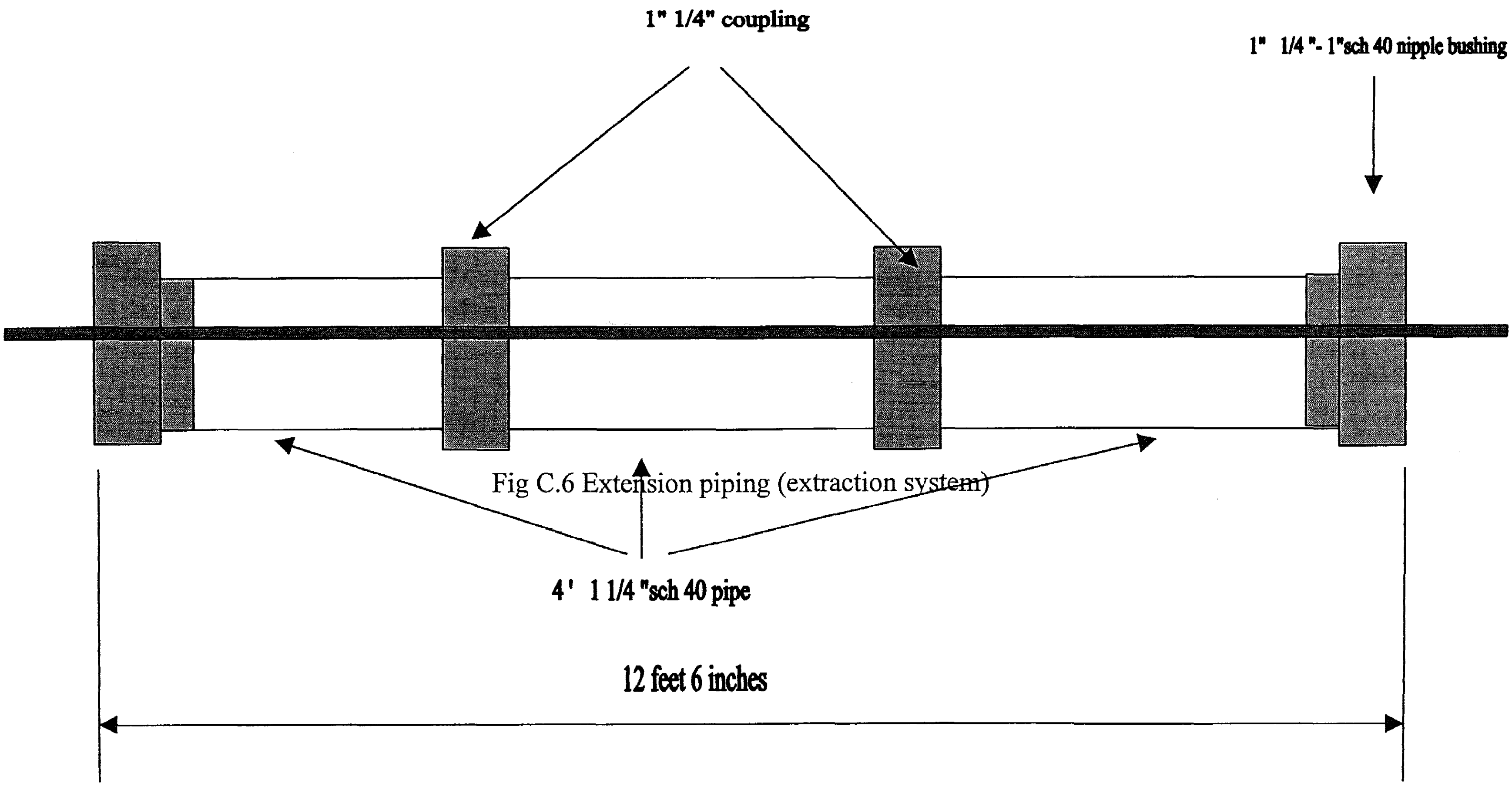


Figure C.5 Extraction Well Setup for Base Value experiments

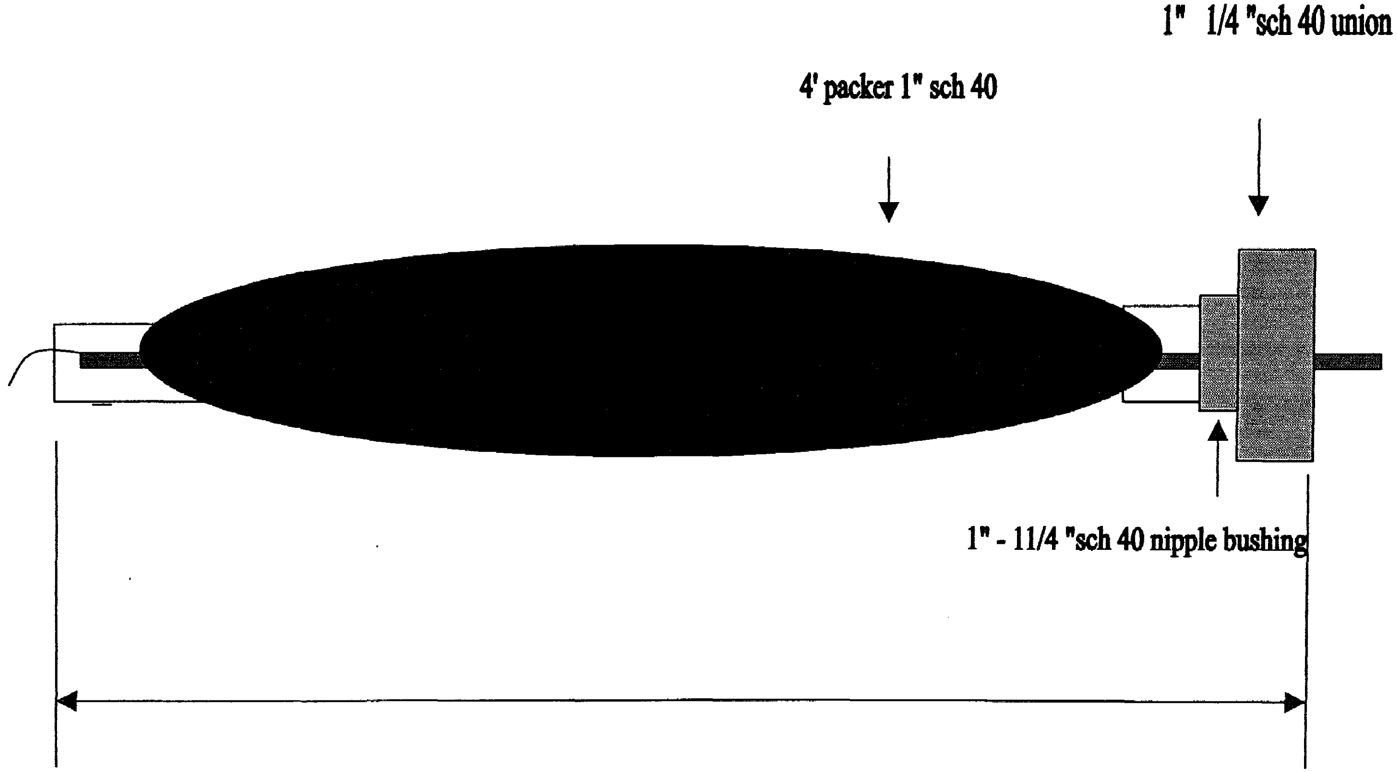


Figure C.6 Packers for Extraction System

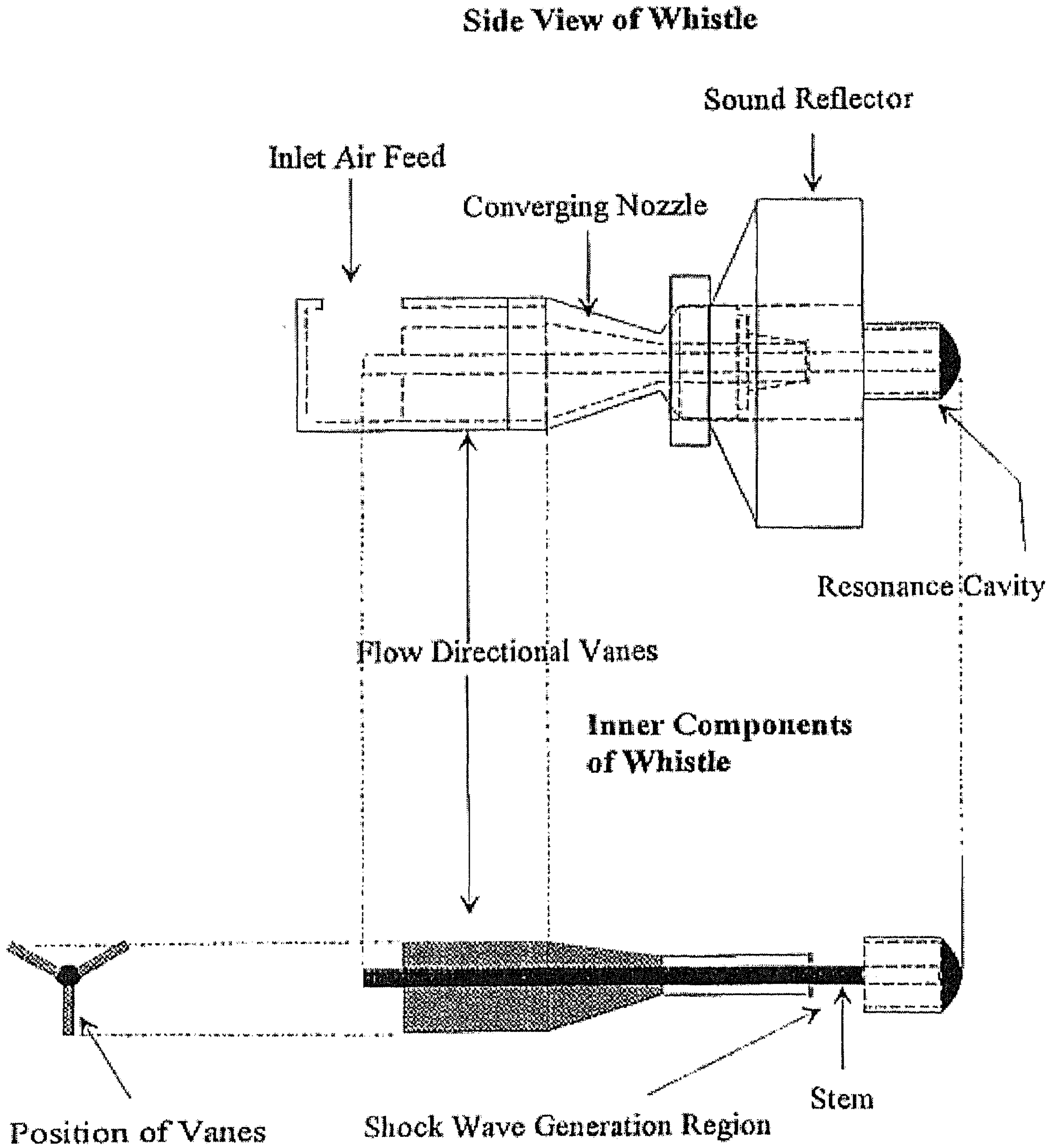


Figure C.7 Detailed Schematic of Whistle
(Source: Fernandez, 1997)

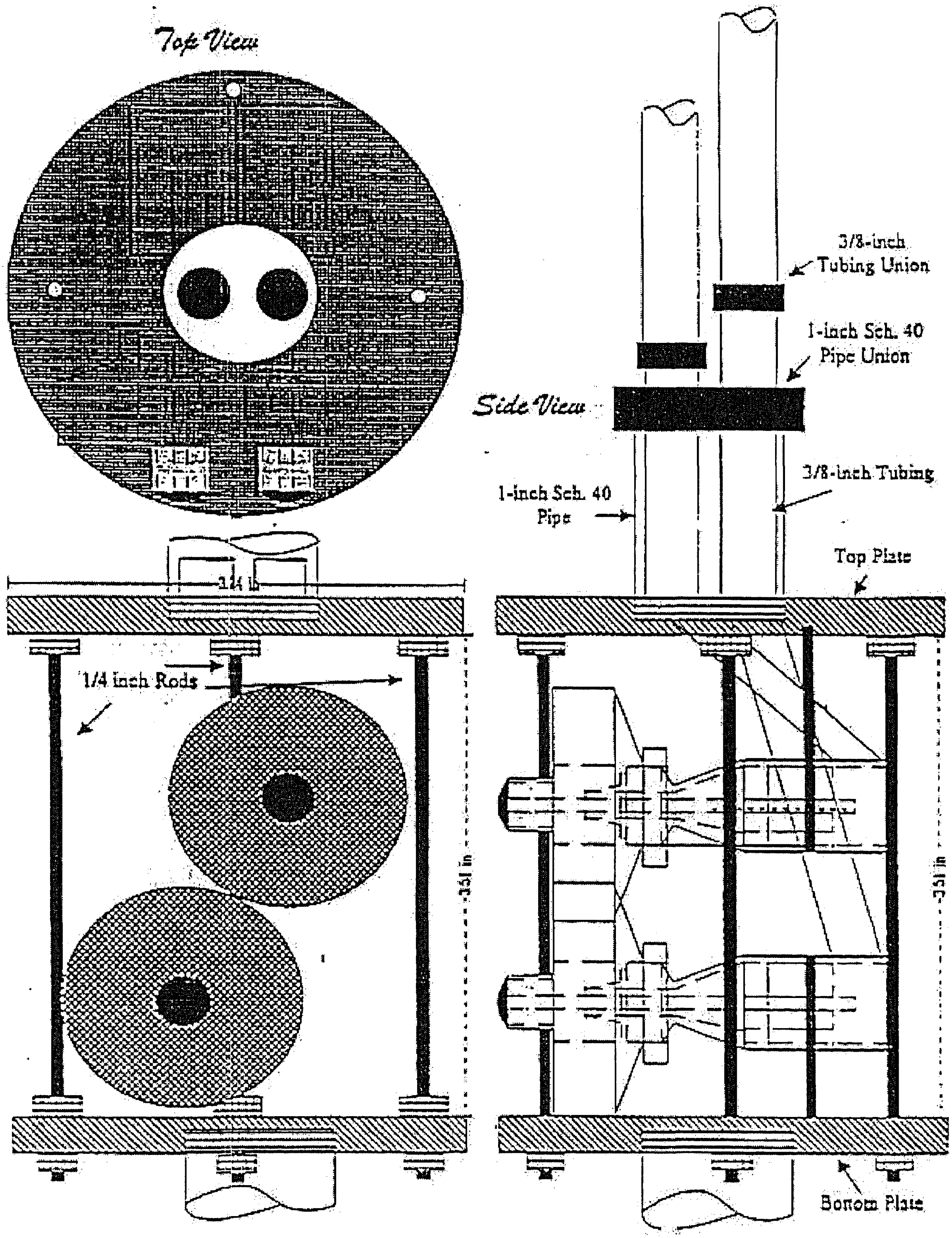


Figure C.8 Schematic of Whistle Assembly when two whistles are used. (Source: Kaleem, 1999)

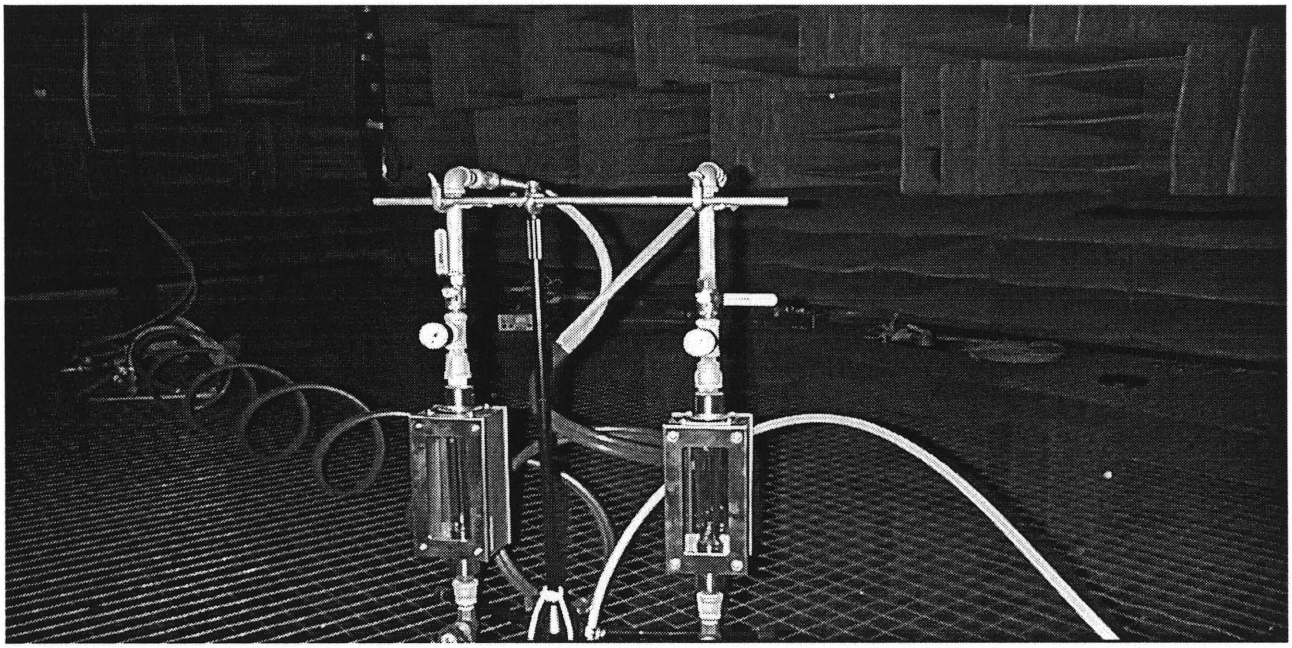


Figure C.9 Photograph of Test 1 – Flowmeter Assembly.

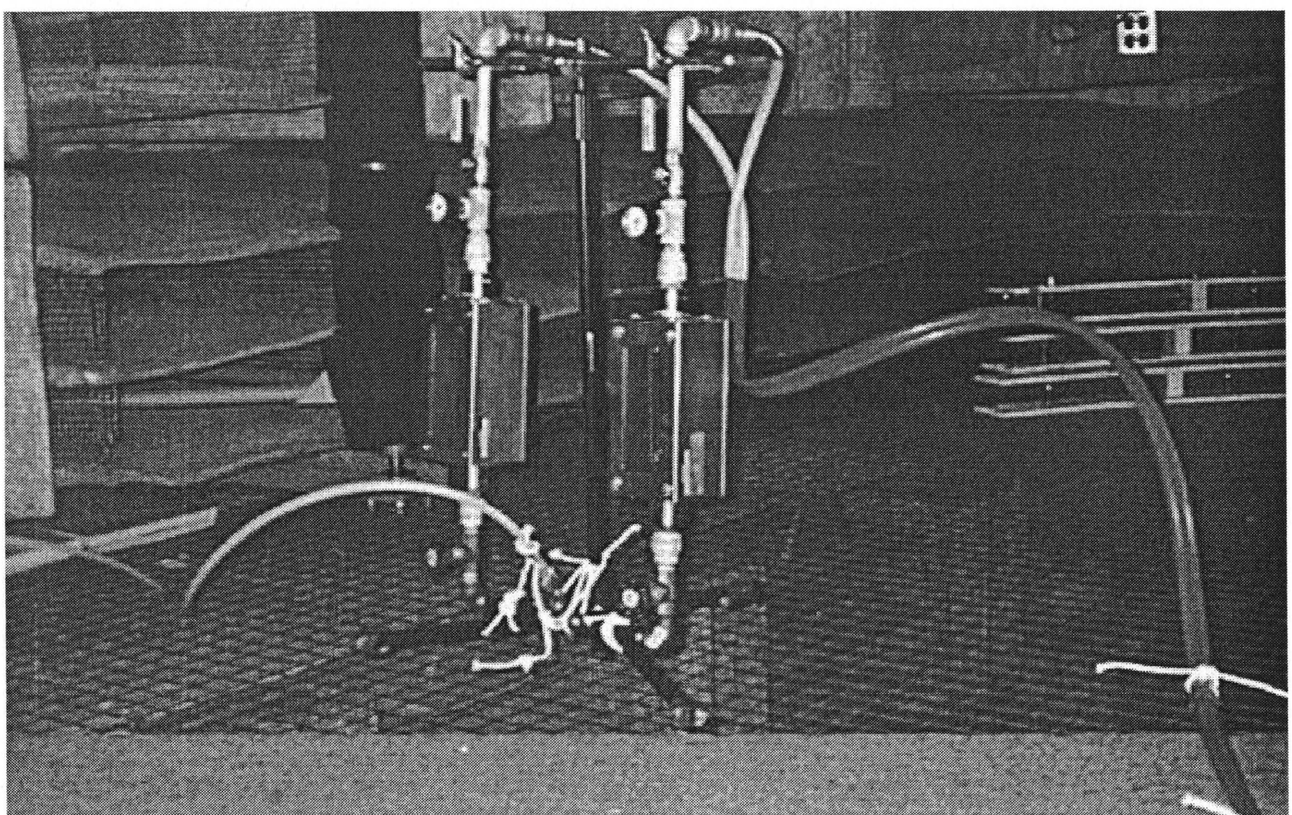


Figure C.10 Photograph of Test 1 – Close-up of the Flowmeter Assembly

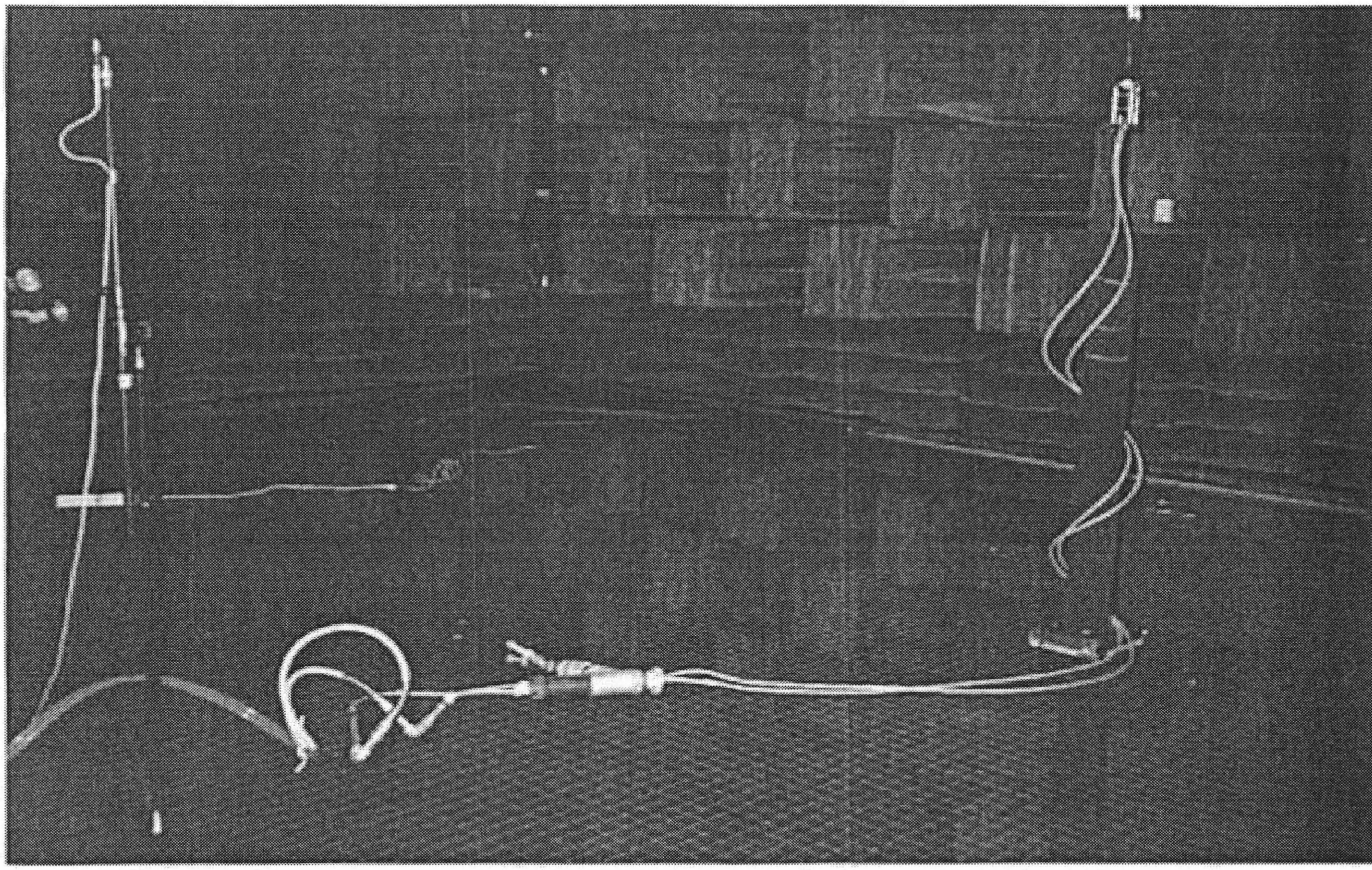


Figure C.12 Photograph of Test 1 – Setup of whistle and microphone.

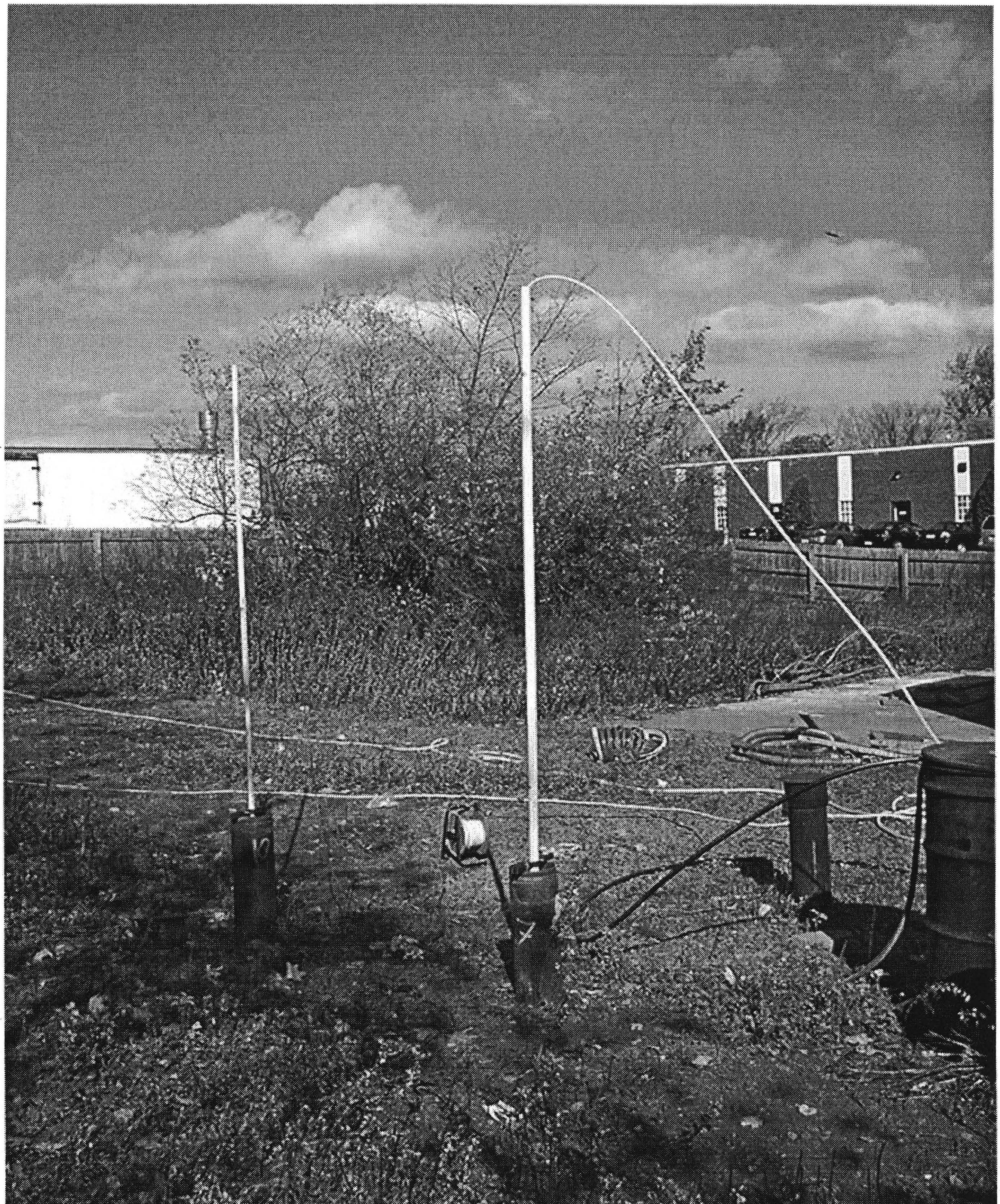


Figure C.13 Photograph of Setup for Field Runs – Injection and Extraction Wells

Figure C.14 Photograph of Setup for Field Runs – Flowmeter, Preamplifier Box, tubing, etc.

Figure C.15 Photograph of Setup for Field Runs – Combined Setup

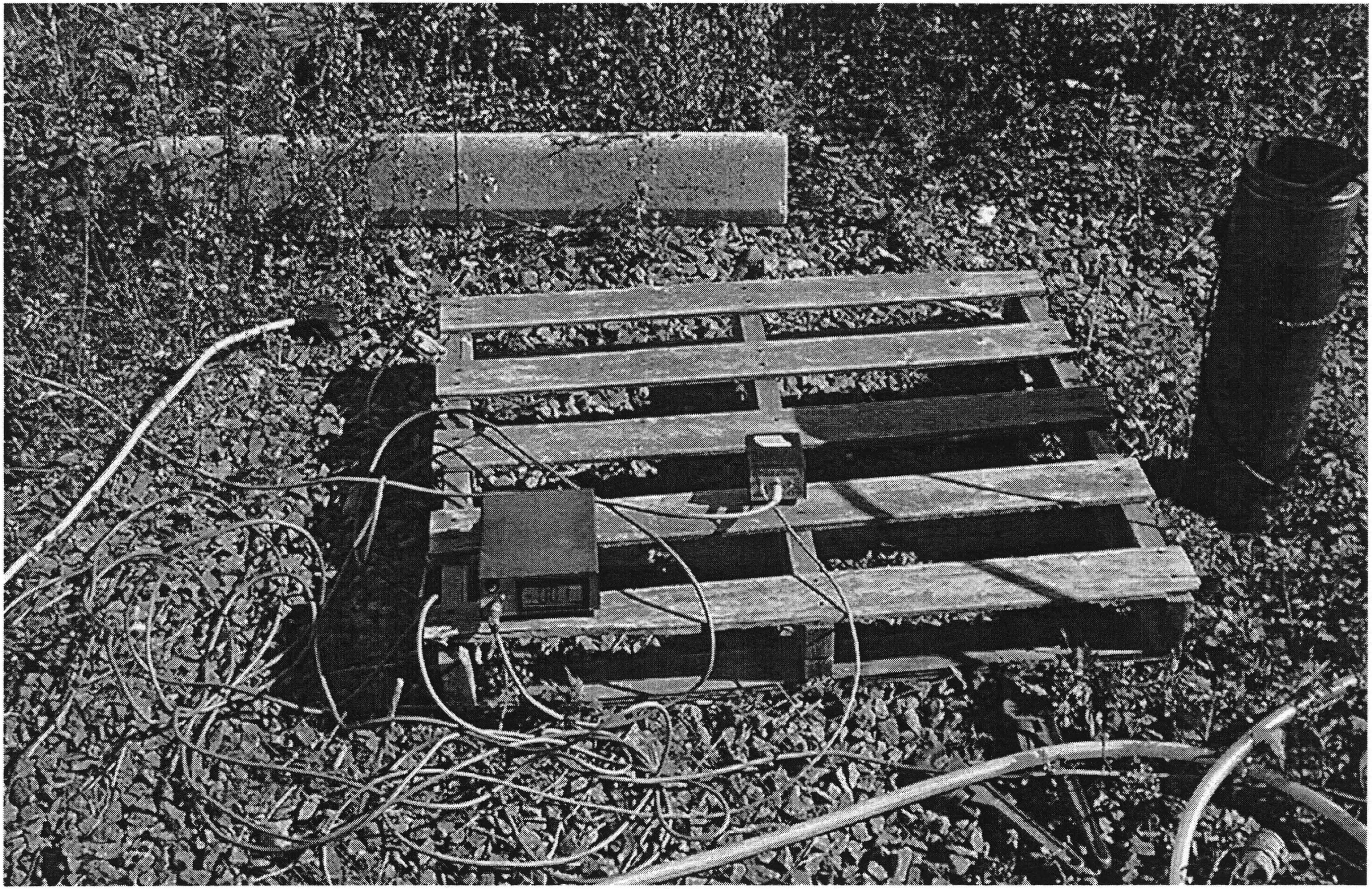
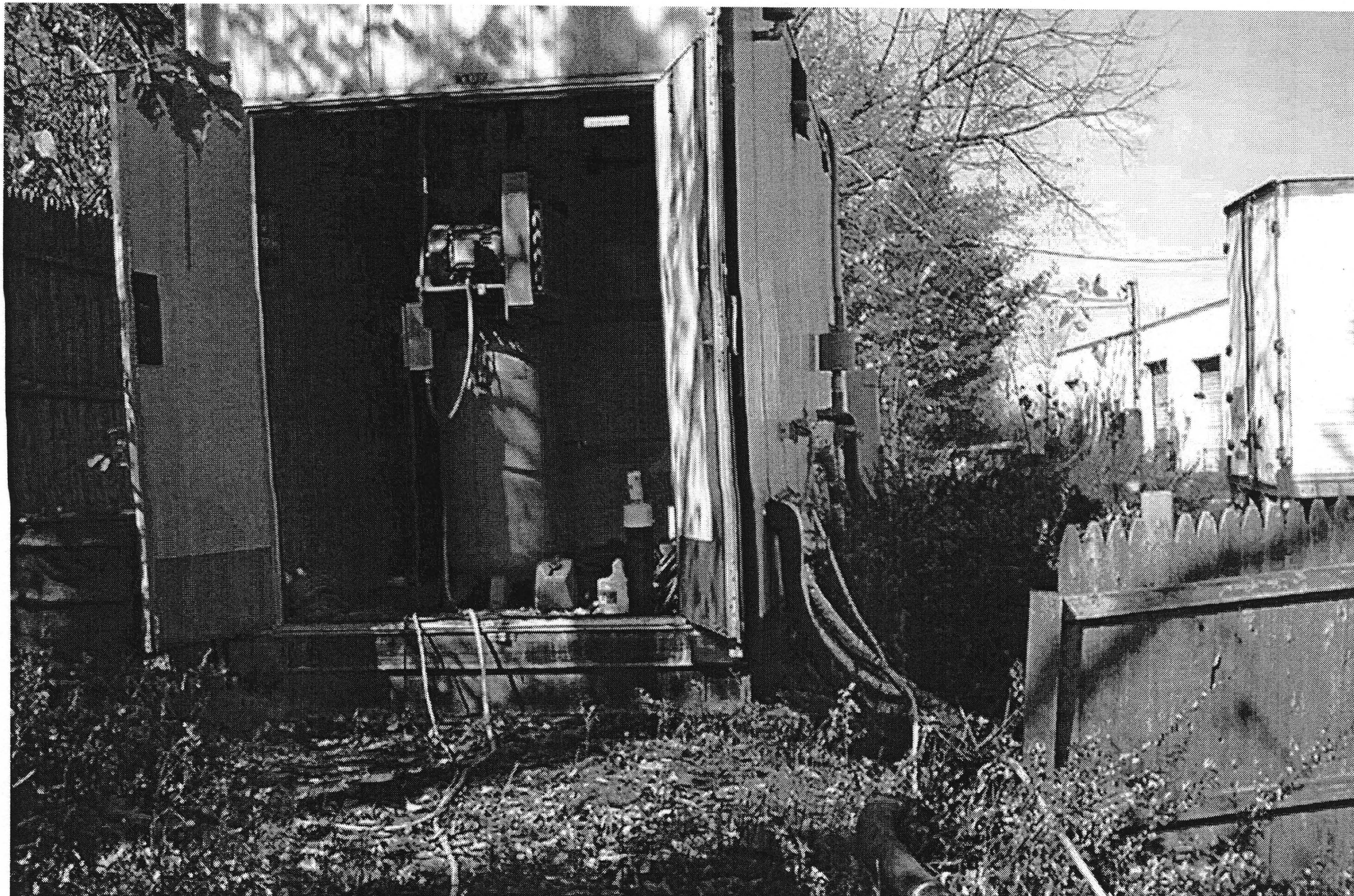


Figure C.16 Photograph of Setup for Field Runs – Close-up of Flowmeter and Pre-amplifier Box



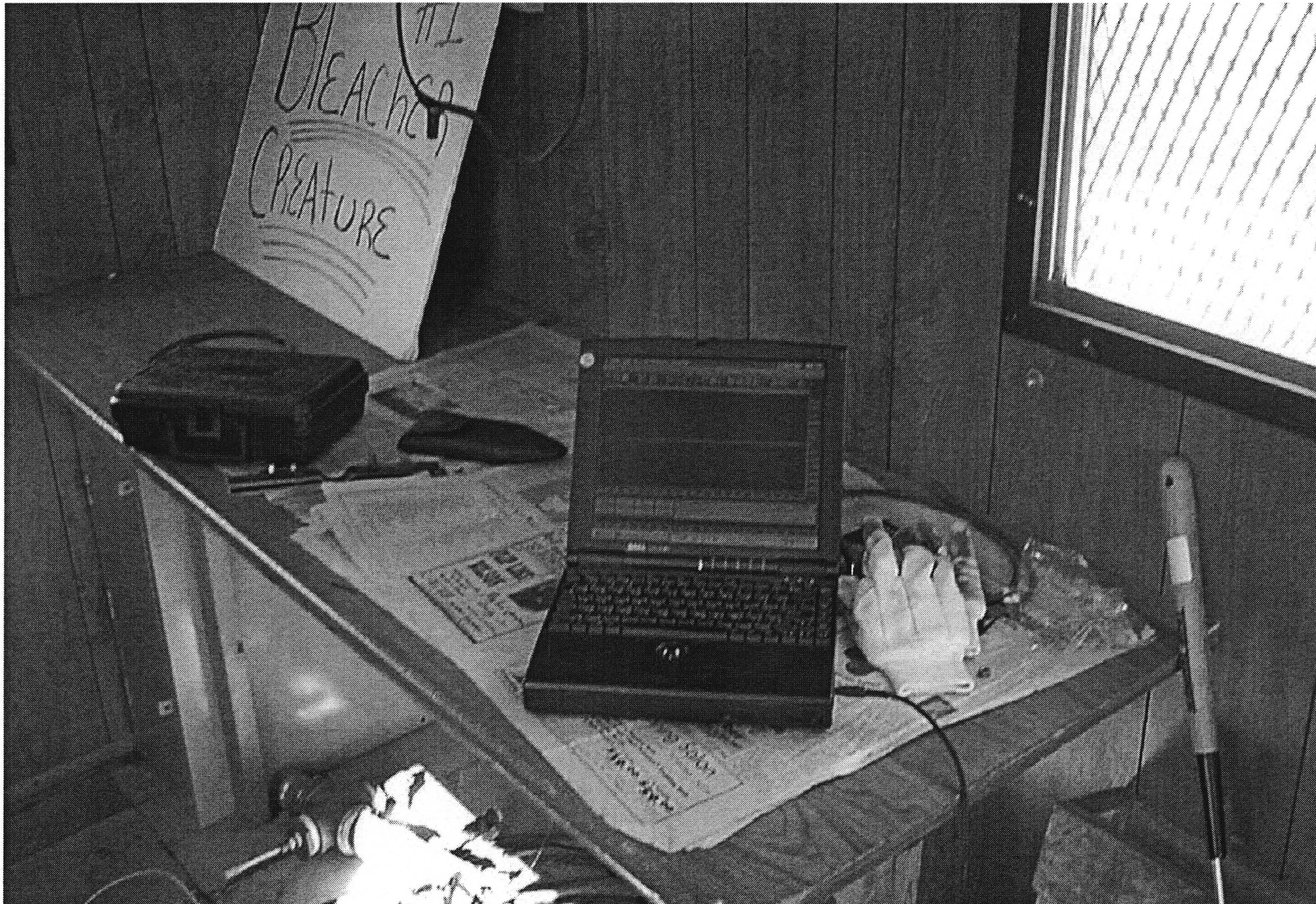


Figure C.18 Photograph of Setup for Field Runs – Laptop in Trailer.

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